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Benchmarking of Canadian Genomics – 1991-2002

Prepared for

Genome Canada

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Executive Summary

The future of Canadian genomics looks bright. The science has reached its cruising speed and the technology has important potential for commercial applications. If Canada plays its cards carefully, it could end up enjoying a position similar to that it currently occupies in biotechnology – that is – not being a giant but being able to play at the same table as the most important players in the field. There are two important strategies that need to be prioritized to develop Canada's comparative advantage:

- Canada should encourage scientists to seek excellence: quality, rather than quantity, is the way forward for Canadian genomics.
- Canada should support innovation in genomics – the intellectual property position of Canada in genomics in strong. It is important to keep the momentum; researchers should be encouraged to patents their inventions and entrepreneurs should be supported in the commercialization of genomic technologies.

Summary of the Findings

- This report provides a quantitative analysis of Canadian genomic science and technology using the Science Citation Index Expanded database produced by Thomson ISI and the United States Patents and Trademark Office (USPTO) patents database.
- Using time series (1991-2002), the report outlines the evolution of genomics at the world and Canadian levels. It uses stationary distributions (3-year and 12-year periods) to compare Canada to other countries as well as Canadian provinces and institutions among themselves.
- Globally, Canada is an important producer of scientific output in genomics at the world level and its production is of a high standard. However, the multiple indicators used in this report converge and suggest that Canada cannot compete against faster-growing countries in terms of number of papers but it will be able to hold its own in the future if it produces increasingly excellent science.
- Canada has an excellent technological position as measured by intellectual property protection: it ranks third at the world level and could be second if continued efforts were made to promote the patenting of Canadian inventions in genomics.

PART I SCIENTIFIC PUBLICATIONS IN GENOMICS

Genome Science at the International Level

- Between 1991 and 2002, papers in genomics increased by close to 60% at the world level, that is, from 35,000 to 55,000 papers per year.
- In terms of the percentage of total papers in genomics in the SCI Expanded database, growth has been somewhat slower (close to 30% growth), that is, from 6% in 1991 to 7.7% in 1998, after which it oscillated between that level and 7.4% of the total number of papers in SCI Expanded.

- Canada ranks 6th at the world level in terms of scientific output between 1991 and 2002. During this period, Canada published 29,178 papers (averaging 2,430 papers per year), which represents close to 5% of the world output in the field.
- Canada's output of papers in genomics did not keep up with the world frontier between 1991 and 2002. In fact, the percentage of the world's papers in genomics written by Canadian authors peaked at 5.2% in 1992 to stabilize between 4.6% and 4.7% of the world's output during the last three years.
- The ranks of the seven most productive countries were perfectly stable over the whole period, but the five smaller contenders demonstrated more volatility.
- The rising star clearly is Spain, which started out in 12th position, moved to 10th in 1997-1999 and then to 8th in 2000-2002.
- Japan has become the clear leader in terms of specialization in genomics. Japan has made a marked improvement on its initial position: it ranked 6th during the 1991-1993 period, third in the 1994-1996 period and moved to first place afterwards. Switzerland and Sweden are strong contenders for second place.
- In terms of scientific impact, the United States and Switzerland both have papers in genomics whose expected impact is considerably higher than that of other countries (19% and 16% higher).
- The impact factor of Canadian papers increased steadily over the period (from 1% to 9% more than the world average).
- Switzerland had the greatest number of citations per paper on average. The United States, the Netherlands and the United Kingdom are also cited significantly more often than other countries are.
- On average, Canada ranks fifth in terms of citations. Importantly though, Germany has overtaken Canada lately and Australia is rapidly closing the gap and might even overtake Canada in the near future.
- Canada has a well-developed network of international collaboration. Canada’s largest collaborator in genomics by far is the United States – it accounts for 63% of Canadian papers written in collaboration. The United Kingdom and France are collaborators of equal importance (10% of Canadian international collaborations in each case).
- Canada's largest international institutional collaborator is Harvard, and following, the University of Washington. Most of the international collaborators are universities, but there are also a number of national research institutions such as the National Cancer Institute in the U.S., CNRS, INSERM and INRA in France, CSIRO in Australia, CNR in Italy, and CSIC in Spain.
- When all scientometric indicators are weighed in, Canada ranks 7th overall with Germany. Canada's position has improved since it ranked 6th during the 1991-1993 period, and finished 5th in the 2000-2002 period (*ex-equo* with France and Germany).

Genome Science in Canada

- At the provincial level, Ontario has the largest number of papers, followed by Quebec, British Columbia and Alberta.
- Inter-provincial collaborations are somewhat marginal in Canadian genomics. Less than 10% of the papers in genomics are by Canadian scientists from different provinces, which contrasts with the more than 40% of papers being written with international collaborators.
- Leading universities are the University of Toronto (4,570 papers), McGill University (3,739 papers), University of British Columbia, University of Alberta, Université Laval and Université de Montréal.
- The leading hospital is the Hospital for Sick Children (1,336 papers). Five other university hospitals are in the 25 leading institutions: Centre hospitalier universitaire de Québec (CHUQ), McGill University Health Centre (MUHC), the University Health Network and Mount Sinai Hospital of Toronto.
- The leading government departments or agencies are Agriculture and Agri-Food Canada (1,026 papers) and the National Research Council Canada (731 papers).
- The most frequent inter-institutional collaborations involve the large Canadian universities and their affiliated hospitals.

PART II TECHNOLOGICAL INVENTIONS IN GENOMICS

- Between 1991 and 2001, the number of patents granted by the USPTO in the field of genomics has grown more than sixfold, increasing from 713 to 4,592 patents per year.
- The percentage of genomic patents relative to the total number of patents granted by the USPTO has also grown considerably, increasing from 0.7% to 2.5%.
- Canada is an important player in the field of genomic inventions. It has nearly as many patents as countries that are much larger have: Germany, the United Kingdom and France.
- Overall, Canada occupies the 5th and 6th ranks over the period, in close competition with France, in terms of number of patents.
- With 36%, Canada has had one of the highest average annual growth rates in patents (ranking 5th in the world).
- During the twelve past years, the number of patents granted to Canada followed a similar pattern to that of papers in genomics by the world as a whole.
- Canada is fourth in terms of the index of specialization in intellectual property in genomics. It is preceded by Australia, the Netherlands and the United Kingdom.
- Citations received for Canadian patents show not only that Canada has many patents in genomics but also that they appear to have a substantial impact on the technological evolution of the field.

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Introduction

The story goes that the term "genomics" was invented in a late-night discussion in a bar located in Bethesda, U.S. It took Dr. Thomas Roderick and his colleagues two or three pitchers of beer to come up with this new term that they meant to encompass sequencing, mapping and the study of "comparative aspects of genomes of various species, their evolution, and how they related to each each other". The merry scientists also thought of genomics as relating to the "genome as a functioning whole beyond just single genes or sequences spread around a chromosomes"[1].

The knowledge and the techniques that led to the development of this field are also quite recent. The discovery of the double helix by James Watson and Francis Crick helped by Maurice Wilkins, and Rosalind Franklin in 1953 opened the door to understanding the inner composition of living beings and how many of their functions are regulated at the molecular level. In 1974 Frederick Sanger invented a nucleic acid sequencing technique[2] while Allan Maxam and Walter Gilbert at Harvard independently discovered a competing technique, thus providing scientists with practical methods to gather insightful information about the structure of the gene.

With the invention of the polymerase chain reaction (PCR) technique by the American molecular biologist Kary Banks Mullis in 1985[3], then working at Cetus, followed by the development of the "shotgun sequencing"[4] technique in 1991 by the National Institute of Health's Mark Adams and Craig Venter, the basic tools were all in place for a rapid progression of genomic. In fact, according to a market survey performed by Business Communications Co. in 2000, the market for genomics-based products and services was estimated at about $2 billion in 1999. The market was expected to grow at an average growth rate of 30% between 2000 and 2004 and to reach more than $8 billion by 2004[5].

Although the field of genomics is highly important not only because of the current levels of investment in research but also because of all the promises it holds, there are few current studies

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[1] Kuska, B. (1998) Beer, Bethesda, and Biology: How "Genomics" Came Into Being. *Journal of the National Cancer Institute*. 90(2): 93.

[2] Frederick Sanger was awarded two Nobel prizes in chemistry for his work on sequencing. The first Nobel was in 1958 for amino acids sequencing and the second in 1980 for his work on nucleic acids sequencing.

[3] Mullis, Kary B. Process for amplifying nucleic acid sequences. U.S. patent 4,683,202, filed October 25, 1985 and granted July 28, 1987; Mullis, K.B, Faloona, F.A., Scharf, S., Saiki, R.K., Horn, G and Erlich, H.A. (1986) Specific enzymatic amplification of DNA in vitro: the polymerase chain reaction. *Cold Spring Harbor Symposia on Quantitative Biology*. PCR allows regions of DNA to be copied several times from a tiny sample and amplifying it so that it can be more easily analysed.

[4] More precisely, the technique is known as Expressed Sequence Tag (EST) sequencing and is now widely used for the discovery and mapping of genes.

[5] Business Communications Co. (2000) *The Genomics Revolution.* Report RB-142.

that compare the level of scientific and technological achievement of leading countries. De Looze and her colleagues have produced some of the more interesting studies[6], but their focus was mainly European and they did not go as far as to suggest a global rank of countries in terms of latter's scientific and technological capabilities. This report aims to fill this gap with the use of scientometric and technometric methods.

In this report, we use a set of keywords that has been defined over the years by the authors of this report in collaboration with genomics experts. These keywords are used to build a basic corpus of papers in genomics extracted from Thomson-ISI's *Science Citation Index Expanded* database and from the United States Patent and Trademark Office database. The methods are described in greater detail in the following section.

The report is divided into two parts. Part I examines how countries compare in terms of scientific output in genomics, while Part II examines their technological performance using patents as an indicator.

Chapter 1 ranks countries in genomics following a series of scientometric indicators such as number of papers, index of specialization, impact factor, number of citations. These indicators are subsequently combined in a multicriteria analysis that aims to provide a synthetic picture of genome science at the international level. Using a combination of absolute and relative indicators, the leading countries in genomics between 1991 and 2002 were 1) U.S.; 2) Switzerland; 3) U.K.; 4) the Netherlands; 5) France; 6) Sweden; 7) Canada; 8) Germany; 9) Japan; 10) Australia; 11) Italy; and 12) Spain.

Chapter 2 examines genome science in Canada. Not surprisingly, Ontario and Quebec have the largest output. The report also examines scientific output and collaboration between institutions and, here again, there is no major surprise: the University of Toronto and McGill are the prominent centres of excellence in genomics in Canada.

Chapter 3 in Part II examines the distribution of intellectual property protection. Using a multicriteria ranking of leading countries in genomic technology, the leading countries rank as follow: 1) U.S.; 2) the Netherlands; 3) Canada; 4) U.K.; 5) Australia, Sweden and Switzerland (*ex-equo*); 8) France; 9) Germany and Japan (*ex-equo*); 11) Spain; and 12) Italy.

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[6] See e.g. Coronini, P.R., Joly, P.-B. and de Looze, M.A. (1997) Genome research: a difficult race. *Biofutur*. (173):14-17.; Bettels, B., Colonna, P., de Looze, M.-A., Nieddu, M. (1999) The patent battle has begun. *Biofutur*. (193): 26-30; de Looze, M.-A. and Ramani, S.V. (1999) Biotechnology patent application in Europe – A look at the differences between French, British, and German patent application trends. *Nature Biotechnology*. 17(1): 83-85; de Looze, M.-A., Coronini, R. and Joly, P.-B. (2001) A note on recent trends in knowledge creation and appropriation thought genomics: a scientometric analysis. *International Journal of Biotechnology*. 3(1-2): 457-480; Ramani, S.V. and de Looze, M.-A. (2002) Country-specific characteristics of patent applications in France, Germany and the UK in the biotechnology sector. *Technology Analysis and Strategic Management*. 14(4): 457-480.

The report shows that although Canada has fared well in the last decade, it is facing mounting pressure from countries that started investing in genomics at a later stage. In fact, Canada will probably not be able to sustain the race to publish more, but it certainly has what it takes to continue competing with other countries on the production of excellent science. Moreover, relative to other countries, Canada has a good position in terms of IP, so one could foresee exciting Canadian developments in genome science and technology.

Methods

Scientometric analysis

This scientometric analysis is based on the use of the Science Citation Index Expanded database produced by Thomson ISI which contains papers from more than 6,000 journals[7]. These journals are considered to be the most important peer-reviewed journals in their respective fields. They reflect significant scientific achievements and are the most widely cited journals in the world (more than 80% of the world's citations). The statistics are drawn from four types of document that are considered to be original contributions to scientific knowledge: articles, notes, reviews and conference proceedings. The tables presented herein refer to these four types of document as "papers". The construction of the dataset is essentially based on the use of keyword-in-title searches. The query used has been fine-tuned over the years and was originally defined by experts named by Genome Canada and by analysts now working at Science-Metrix. The keywords have been tried and tested and select papers in core and peripheral genomics (such as papers in molecular biology that touch upon the genome).

The resulting dataset was used to produce detailed statistics based on the following indicators:

Number of papers - Number of scientific papers written by authors located in a given geographical, geopolitical or organizational entity (e.g. countries, cities or institutions).

Index of specialization - This is an indicator of the intensity of research in a given geographic or organizational entity relative to the overall output for a given reference. For example, if the percentage of Canadian papers (the geographic entity) in the field of genomics is greater than the percentage of papers in this field at the world level (the reference), then Canada is said to be specializing in this field.

Average relative impact factor - This indicator is a proxy for the quality of the journals in which papers are published. It is based on a calculation of citations received per journal. An average is calculated through the assignment of a journal impact factor to each paper belonging to a given geographic or organizational entity.

Average relative citation – The average number of citations received for each paper was counted for the year in which they were made and for the two years that followed. For papers published in 1990, for example, citations received in 1990, 1991 and 1992 were counted. The only exception is the year 2001, which comprises a citation window of two years, and 2002, which contains a citation window of one year. The count is relative to the average number of citations in the specialty of the paper.

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[7] Data derived from information prepared by the Institute for Scientific Information, Inc. (ISI, Philadelphia, Pennsylvania, USA).

Technometric analysis

Patents are often used as a measure of invention despite several well-known disadvantages associated with their use:

- **incompleteness**: many inventions are not patented since patenting is only one way of protecting an invention;
- **inconsistency in quality**: the importance and value of patented inventions vary considerably;
- **inconsistency across industries and fields**: industries and fields vary considerably in their propensity to patent inventions;
- **inconsistency across countries**: inventors from different countries have a different propensity to patent inventions, and countries have different patent laws.

Despite these limits, patents are widely used to compare the level of technological development of different geographic and organizational entities. This report uses the United States Patents and Trademark Office (USPTO) database. Its data are widely used to measure invention, since the USPTO is one of the largest repertories of patented inventions in the world. Because the U.S. is the largest market in the world, the most important inventions tend to be patented there. Although the USPTO database presents an obvious bias towards the U.S., it is still a potent tool for comparing other countries. The database used by Science-Metrix contains information on all the patents granted by the USPTO since 1976.

The patent dataset was constructed using keyword-in-title and keyword-in-abstract queries. The statistics presented here are for utility patents granted (that is, not for patent applications). ·The keywords were defined in collaboration with Genome Canada's scientific committee, and numerous refinements were made over the years.

Unlike scientific publications, patents possess two fields that contain bibliographic information relevant to the calculation of where the patent originates: the inventor field and the assignee field. These fields can be used to compute statistics on two different indicators, namely, invention and intellectual property (IP). The majority of patents are owned by corporations, and their addresses, which appear in the assignee field, are used to compute the geographical location of the ownership of IP. In some cases, where an individual is the owner of the IP, the address of this owner is used to compute the location of the IP. For the sake of simplicity, this report presents data on IP only.

Citations received for each patent were counted for the year in which they were granted and the two years that followed. For patents granted in 1990, for example, citations received in 1990, 1991 and 1992 were counted. The only exception is the year 2001, which comprises a citation window of two years, and 2002, which contains a citation window of one year.

Data that is weighted per capita at the country level uses population statistics made by the U.S. Census Bureau. These statistics present annual data for every country estimated at mid-year.

PART I
SCIENTIFIC PUBLICATIONS IN GENOMICS AT THE WORLD LEVEL

1# Genome Science at the International Level

This section presents data on the global rate of growth of scientific papers written in the field of genomics at the world level (Section 1.1). It subsequently benchmarks Canadian scientific output against that of other leading countries in general terms (Section 2).

1.1# Global trends in genome science

Figure 1 shows that the number of papers in genomics grew steadily until 1998 when it reached cruising speed. The number of scientific papers grew from about 35,000 in 1991 to more than 55,000 in 2002, an increase of nearly 60% over the twelve-year period. In terms of the percentage of total papers in the SCI Expanded database, growth has been somewhat slower, that is, from 6% to 7.7% in 1998 (close to 30% growth), after which it oscillated between that level and 7.4% of the total number of papers in SCI Expanded.

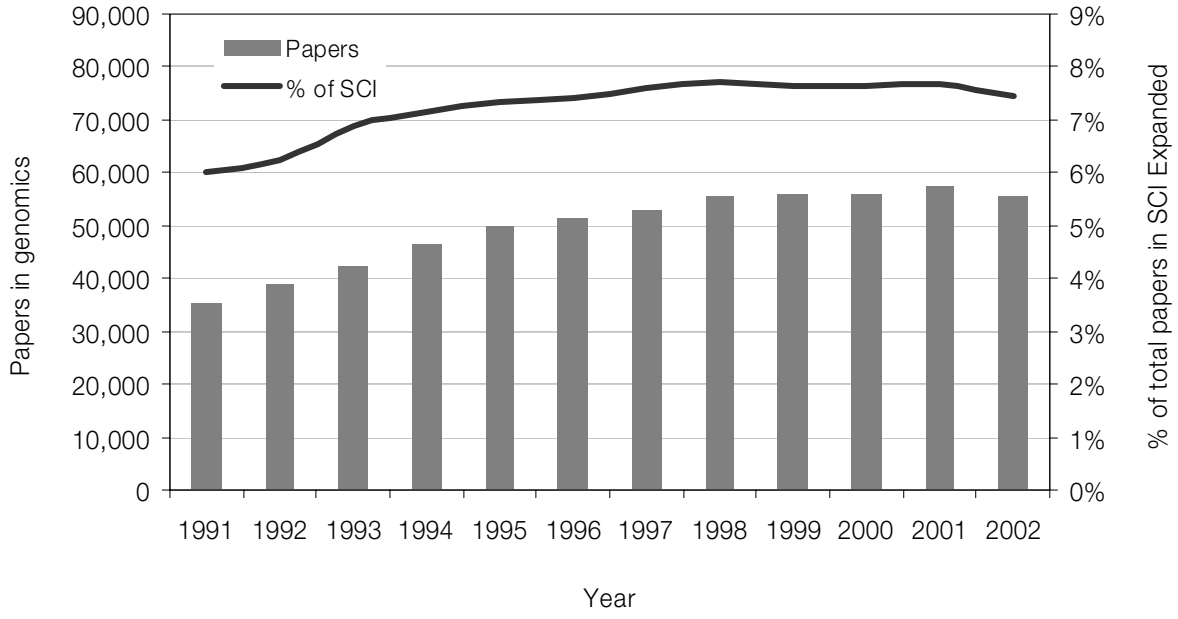
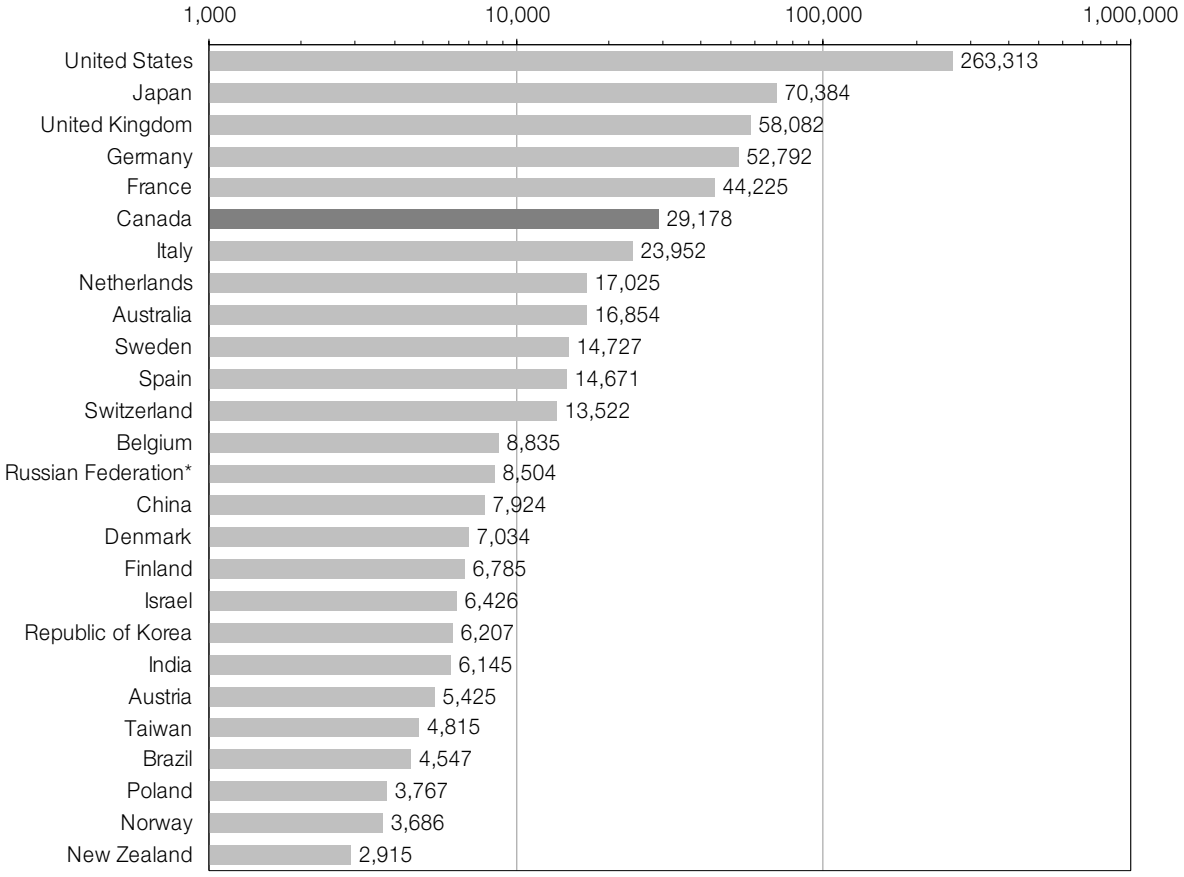


Figure 1 Papers in genomics in SCI Expanded, 1991-2002
Source: Compiled by Science-Metrix from data prepared by ISI Thomson.

Figure 2 shows that Canada's output of papers in genomics during the last twelve years is consistent with the place it occupies within the G7 countries. In fact, the G7 economic countries are also the G7 genomic countries. Data presented in Section 1.2 show that during the last twelve years, Canada consistently ranked 6th among the twelve leading countries when considering four three-year periods. In fact, the ranking of the seven leading countries was highly stable, and everyone kept the same rank.

As one can see in Figure 2, there is a discontinuity in the number of papers published in genomics by the twelve most active countries: the number of papers by countries following Switzerland is substantially lower than for the twelve leaders. Given this discontinuity in the rate of publication, the detailed benchmarking of countries in genomics (Section 1.2) will compare the performance of the twelve most active countries in genomics.



* Papers for 1993-2002 in the case of the Russian Federation

Figure 2 Papers in genomics by leading countries (log scale), 1991-2002
Source: Compiled by Science-Metrix from data prepared by ISI Thomson.

Canada's output of papers in genomics did not keep up with the world frontier between 1992 and 2002: the percentage of the world's papers in genomics written by Canadian authors peaked at 5.2% in 1992 to stabilize between 4.6% and 4.7% of the world's output during the last three years. Since Canadian output in genomics stabilized at slightly more than 2,500 papers per year from 1995 onwards, this diminishing proportion of papers by Canadian scientists is due to the faster rate of growth by other countries. In fact, this is shown in Figure 3, which reveals that in the group of the 24 leading countries in genomics, Canada ranks among those with the lowest average annual growth rate. However, one has to note that nearly all the leading countries (e.g. U.S., United

Kingdom) experienced slow growth in comparison with countries that published less papers during the same period.

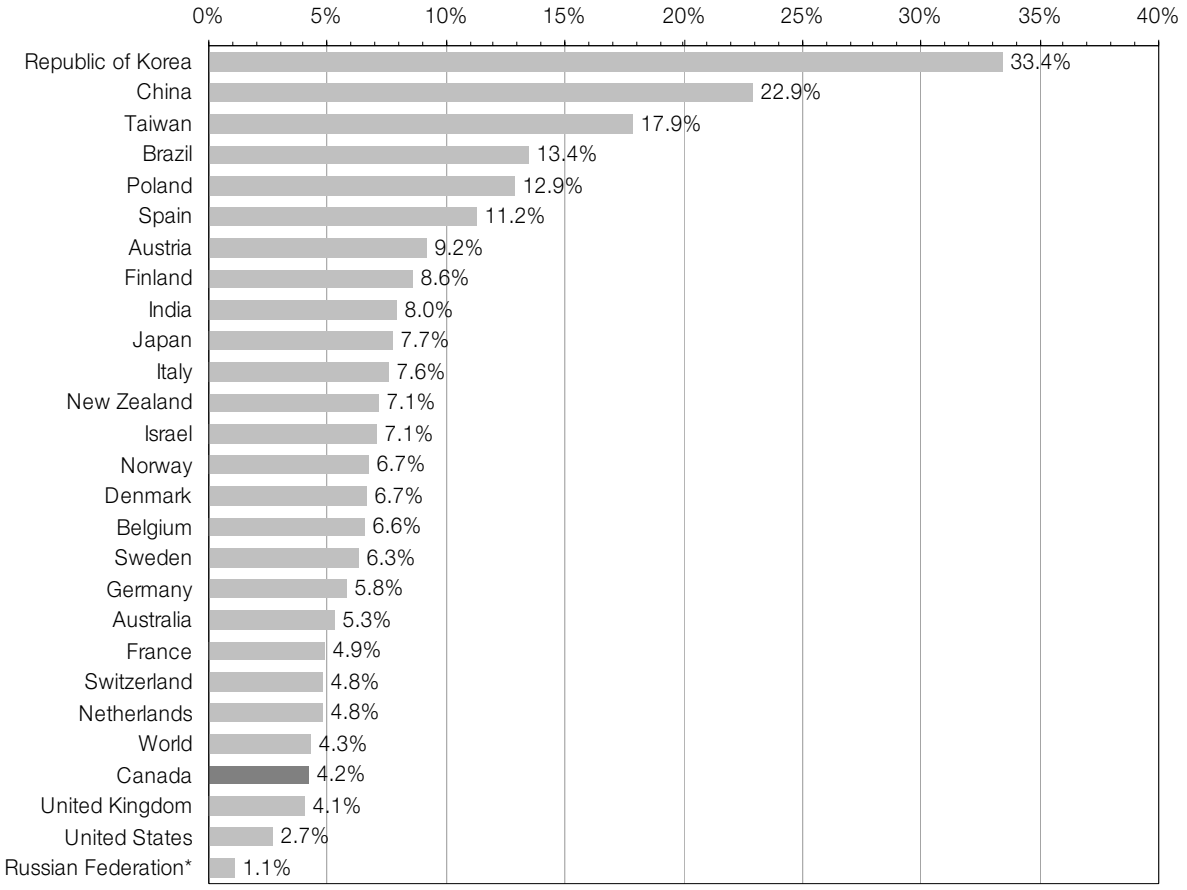


Figure 3 Average yearly growth of papers by country, 1991-2002
Source: Compiled by Science-Metrix from data prepared by ISI Thomson.

1.2# Benchmarking Canada in genome science

This section aims to benchmark leading countries using five evaluation criteria:

- # Number of scientific papers in genomics in SCI Expanded
- # Number of papers per capita
- # Index of specialization
- # Average relative impact factor
- # Average relative citations

The factors are subsequently combined for a multicriteria benchmarking of leading countries. This benchmarking is based on a period of twelve years, which in turn is divided into four three-year periods to examine the evolution of the field in the leading countries.

1.2.1# Number of scientific papers in genomics in SCI Expanded

Table I shows that the number of papers grew rapidly at the world level after the first period and continued to grow afterwards, although at a much lower rate during the last two periods. Importantly, the output of many leading countries stabilized at more or less the same level as that observed during the 1994-1996 period. In the United States, the United Kingdom, France, Canada, the Netherlands and Switzerland, the number of publications during the last period is actually lower than during the preceding three years. Canada experienced rapid growth between the first and second, and its output peaked during the 1997-1999 period.

Table I Number of papers by leading countries in genomics, 1991-2002

Country	1991-1993	1994-1996	1997-1999	2000-2002	1991-2002
United States	55,510	67,983	70,237	69,583	263,313
Japan	11,352	16,309	20,608	22,115	70,384
United Kingdom	11,318	14,500	16,151	16,113	58,082
Germany	9,035	12,529	15,373	15,855	52,792
France	8,271	11,241	12,523	12,190	44,225
Canada	5,862	7,483	7,967	7,866	29,178
Italy	3,912	5,704	6,958	7,378	23,952
Netherlands	3,264	4,254	4,772	4,735	17,025
Australia	3,060	4,048	4,822	4,924	16,854
Sweden	2,675	3,600	4,138	4,314	14,727
Spain	1,986	3,049	4,536	5,100	14,671
Switzerland	2,436	3,498	3,905	3,683	13,522
World	116,259	147,781	164,459	168,962	597,461

Source: Compiled by Science-Metrix from data prepared by ISI Thomson.

Table II ranks the twelve leading countries according to their number of publications in genomics during the four three-year periods and for the twelve-year period as a whole. As one can see, the

ranks were perfectly stable over the whole period for the seven most productive countries, but the smaller contenders demonstrated more volatility. For instance, the Netherlands ranked 8th initially, then moved to 9th rank during the 1997-1999 period and to 10th rank during the 2000-2002 period. The rising star clearly is Spain, which started out in 12th position, moved to 10th in 1997-1999 and to 8th in 2000-2002.

Table II Ranking of leading countries according to the number of papers in genomics, 1991-2002

Rank	1991-1993	1994-1996	1997-1999	2000-2002	1991-2002
1	U.S.	U.S.	U.S.	U.S.	U.S.
2	Japan	Japan	Japan	Japan	Japan
3	U.K.	U.K.	U.K.	U.K.	U.K.
4	Germany	Germany	Germany	Germany	Germany
5	France	France	France	France	France
6	Canada	Canada	Canada	Canada	Canada
7	Italy	Italy	Italy	Italy	Italy
8	Netherlands	Netherlands	Australia	Spain	Netherlands
9	Australia	Australia	Netherlands	Australia	Australia
10	Sweden	Sweden	Spain	Netherlands	Sweden
11	Switzerland	Switzerland	Sweden	Sweden	Spain
12	Spain	Spain	Switzerland	Switzerland	Switzerland

Source: Compiled by Science-Metrix from data prepared by ISI Thomson.

1.2.2# Number of papers per capita

The number of papers per capita is one way of relating a country's scientific production to its size. One can see that several smaller European countries show that they have a strong per capita output compared to that of the larger countries (Table III). In particular, Switzerland and Sweden are clearly in a league of their own. The United Kingdom and Australia, which started with a relatively low level of productivity, have been increasing their per capita output significantly. Globally, Canada has a per capita output that is highly similar to that of the United States and that of Australia.

Canada ranked 5th during the first three periods and slipped to 6th rank during the 2000-2002 period (Table IV). Few countries have moved in terms of their ranking during the periods: the United Kingdom and Australia have moved up somewhat in the ranks, and the U.S. has moved down (initially ranking 3rd but moving down to 7th from the third time period onwards).

Table III Number of papers per million inhabitants by leading countries in genomics, 1991-2002

Country	1991-1993	1994-1996	1997-1999	2000-2002	1991-2002
Switzerland	116	163	180	169	157
Sweden	103	136	156	162	139
Netherlands	72	92	101	99	91
United Kingdom	65	83	91	90	82
United States	72	85	85	81	81
Canada	68	84	87	83	81
Australia	58	74	86	85	76
France	48	64	71	68	63
Germany	37	51	62	64	54
Japan	30	43	54	58	47
Italy	23	33	40	43	35
Spain	17	26	38	42	31
World	7	9	9	9	9

Source: Compiled by Science-Metrix from data prepared by ISI Thomson.

Table IV Ranking of leading countries according to their per capita number of papers in genomics, 1991-2002

Rank	1991-1993	1994-1996	1997-1999	2000-2002	1991-2002
1	Switzerland	Switzerland	Switzerland	Switzerland	Switzerland
2	Sweden	Sweden	Sweden	Sweden	Sweden
3	U.S.	Netherlands	Netherlands	Netherlands	Netherlands
4	Netherlands	U.S.	U.K.	U.K.	U.K.
5	Canada	Canada	Canada	Australia	U.S.
6	U.K.	U.K.	Australia	Canada	Canada
7	Australia	Australia	U.S.	U.S.	Australia
8	France	France	France	France	France
9	Germany	Germany	Germany	Germany	Germany
10	Japan	Japan	Japan	Japan	Japan
11	Italy	Italy	Italy	Italy	Italy
12	Spain	Spain	Spain	Spain	Spain

Source: Compiled by Science-Metrix from data prepared by ISI Thomson.

1.2.3# Index of specialization

The index of specialization provides an appreciation of the intensity of a country's scientific output in a given field relative to its overall scientific output. Japan has become the clear leader in terms of specialization in genomics. Japan has made a marked improvement on its initial position: it ranked 6th during the 1991-1993 period, 3rd in the 1994-1996 period and moved to first place afterwards. Switzerland and Sweden are strong contenders for the second place. The specialization indicator clearly shows that in the past, Canada did not produce as much in genomics as one could have

expected it to given its share of the world scientific output in general. Over the twelve-year period examined here, Canada is last, save Spain, in terms of the index of specialization (Table V). Nevertheless, the data shows that Canada has improved its score since it ranked 10th between 1997 and 1999 and moved to the 9th rank in the 2000-2002 period (Table VI). Given the accrued effort in genomics following Genome Canada's substantial injection of funds into the field, one can expect that Canada's index of specialization will continue to increase over time.

Table V Index of specialization of leading countries in genomics, 1991-2002

Country	1991-1993	1994-1996	1997-1999	2000-2002	1991-2002
Japan	1.19	1.27	1.36	1.40	1.32
Switzerland	1.31	1.38	1.29	1.20	1.29
Sweden	1.29	1.28	1.26	1.27	1.27
United States	1.22	1.23	1.21	1.20	1.21
France	1.25	1.25	1.19	1.15	1.20
Netherlands	1.20	1.15	1.14	1.10	1.15
Germany	1.01	1.06	1.07	1.07	1.06
Italy	1.04	1.05	1.06	1.04	1.05
United Kingdom	1.10	1.05	1.05	1.02	1.05
Australia	1.07	1.02	1.03	1.02	1.04
Canada	0.97	1.00	1.04	1.04	1.01
Spain	0.87	0.88	1.00	1.00	0.96
World	1.00	1.00	1.00	1.00	1.00

Source: Compiled by Science-Metrix from data prepared by ISI Thomson.

Table VI Ranking of leading countries according to their index of specialization in genomics, 1991-2002

Rank	1991-1993	1994-1996	1997-1999	2000-2002	1991-2002
1	Switzerland	Switzerland	Japan	Japan	Japan
2	Sweden	Sweden	Switzerland	Sweden	Switzerland
3	France	Japan	Sweden	U.S.	Sweden
4	U.S.	France	U.S.	Switzerland	U.S.
5	Netherlands	U.S.	France	France	France
6	Japan	Netherlands	Netherlands	Netherlands	Netherlands
7	U.K.	Germany	Germany	Germany	Germany
8	Australia	Italy	Italy	Italy	Italy
9	Italy	U.K.	U.K.	Canada	U.K.
10	Germany	Australia	Canada	Australia	Australia
11	Canada	Canada	Australia	U.K.	Canada
12	Spain	Spain	Spain	Spain	Spain

Source: Compiled by Science-Metrix from data prepared by ISI Thomson.

1.2.4# Average relative impact factor

The average relative impact factor is used to evaluate the expected impact of papers from each country compared to other papers in genomics at the world level. This indicator provides a proxy for the quality of the journals in which papers are published: the higher the index value, the higher the average quality of a journal is. For instance, the United States and Switzerland both have papers in genomics whose expected impact is considerably higher than that of other countries (19% and 16% higher) (Table VII). They are followed by the United Kingdom and the Netherlands which both publish papers in genomics in journals that are cited 7% more than the world average in genomics. Canada published in journals that are cited 6% more than the world average in genomics over the whole period. Although the impact factor of Canadian papers increased steadily over the period, that of the United Kingdom grew faster still, which explains why Canada slid from 3rd rank in the first period to 4th in the second period and 5th during the last two three-year periods (Table VIII).

Table VII Average relative impact factor of leading countries in genomics, 1991-2002

Country	1991-1993	1994-1996	1997-1999	2000-2002	1991-2002
United States	1.18	1.19	1.20	1.19	1.19
Switzerland	1.14	1.15	1.19	1.16	1.16
Netherlands	0.96	1.05	1.10	1.13	1.07
United Kingdom	1.00	1.02	1.09	1.12	1.07
Canada	1.01	1.05	1.07	1.09	1.06
France	0.96	0.96	1.02	1.05	1.00
Germany	0.93	0.96	0.98	1.02	0.98
Australia	0.92	0.94	0.96	0.98	0.95
Sweden	0.90	0.95	0.97	0.97	0.95
Italy	0.85	0.92	0.94	0.96	0.93
Spain	0.87	0.92	0.94	0.95	0.93
Japan	0.87	0.87	0.87	0.87	0.87
World	1.00	1.00	1.00	1.00	1.00

Source: Compiled by Science-Metrix from data prepared by ISI Thomson.

Table VIII Ranking of leading countries according to their average relative impact factor in genomics, 1991-2002

Rank	1991-1993	1994-1996	1997-1999	2000-2002	1991-2002
1	U.S.	U.S.	U.S.	U.S.	U.S.
2	Switzerland	Switzerland	Switzerland	Switzerland	Switzerland
3	Canada	Netherlands	Netherlands	Netherlands	Netherlands
4	U.K.	Canada	U.K.	U.K.	U.K.
5	France	U.K.	Canada	Canada	Canada
6	Netherlands	France	France	France	France
7	Germany	Germany	Germany	Germany	Germany
8	Australia	Sweden	Sweden	Australia	Australia
9	Sweden	Australia	Australia	Sweden	Sweden
10	Japan	Italy	Italy	Italy	Italy
11	Spain	Spain	Spain	Spain	Spain
12	Italy	Japan	Japan	Japan	Japan

Source: Compiled by Science-Metrix from data prepared by ISI Thomson.

1.2.5# Average relative citation

Whereas the impact factor provides a measure of the average number of citations received by journals, and thus an expected citation score, average relative citations provide an indicator of the number of times papers by a country are effectively cited relative to the world average. Again, a score above one denotes that a country's papers are cited more often than the average paper in genomics.

Whereas the U.S. had the highest number of *expected citations* (i.e. impact factor), it is Switzerland that had the greatest number of *effective citations* by paper on average (Table IX). On average, the papers of the United States, the Netherlands and the United Kingdom are also cited significantly more often than that of other countries. Those of Canada, Germany, France, Sweden and Australia are also cited more often, on average, than the world average paper is. Australia has increased its number of average citations per paper steadily and might even overtake Canada in the near future. Over the twelve-year period, Canada ranked fifth in terms of average relative citations. Importantly though, Germany has overtaken Canada lately, and Australia is rapidly closing the gap (Table X).

Table IX Average relative citations of leading countries in genomics, 1991-2002

Country	1991-1993	1994-1996	1997-1999	2000	1991-2000
Switzerland	1.19	1.32	1.35	1.37	1.32
United States	1.23	1.24	1.25	1.27	1.25
Netherlands	1.17	1.20	1.21	1.28	1.22
United Kingdom	1.14	1.15	1.21	1.26	1.20
Canada	1.02	1.07	1.12	1.10	1.08
Germany	0.99	1.04	1.03	1.11	1.05
France	1.00	1.04	1.03	1.06	1.03
Sweden	0.98	1.06	1.02	1.03	1.03
Australia	0.91	0.98	1.01	1.09	1.01
Italy	0.80	0.93	0.91	0.91	0.90
Spain	0.71	0.77	0.88	0.92	0.85
Japan	0.86	0.82	0.83	0.85	0.84
World	1.00	1.00	1.00	1.00	1.00

Source: Compiled by Science-Metrix from data prepared by ISI Thomson.

Table X Ranking of leading countries according to average relative citations, 1991-2002

Rank	1991-1993	1994-1996	1997-1999	2000	1991-2000
1	U.S.	Switzerland	Switzerland	Switzerland	Switzerland
2	Switzerland	U.S.	U.S.	Netherlands	U.S.
3	Netherlands	Netherlands	U.K.	U.S.	Netherlands
4	U.K.	U.K.	Netherlands	U.K.	U.K.
5	Canada	Canada	Canada	Germany	Canada
6	France	Sweden	Germany	Canada	Germany
7	Germany	Germany	France	Australia	France
8	Sweden	France	Sweden	France	Sweden
9	Australia	Australia	Australia	Sweden	Australia
10	Japan	Italy	Italy	Spain	Italy
11	Italy	Japan	Spain	Italy	Spain
12	Spain	Spain	Japan	Japan	Japan

Source: Compiled by Science-Metrix from data prepared by ISI Thomson.

1.2.6# Multicriteria analysis

In order to obtain a global assessment of the leading countries in genomics, one can resort to a multicriteria ranking. The criteria considered are number of papers, number of papers per capita, index of specialization, average relative impact factor and average relative citations. During the twelve-year period considered here, the United States and Switzerland were the clear winners (Table XI). The bronze goes to the Netherlands, and the fourth place is occupied by the United Kingdom. France is fifth, Sweden sixth and Canada seventh with Germany.

Table XI Multicriteria ranking of leading countries in genomics, 1991-2002

Rank	1991-1993	1994-1996	1997-1999	2000-2002	1991-2002
1	U.S.	U.S.	U.S.	U.S.	U.S.
2	Switzerland	Switzerland	Switzerland	Switzerland	Switzerland
3	U.K.	Netherlands	U.K.	Netherlands	Netherlands
4	Netherlands	U.K.	Netherlands	U.K.	U.K.
5	France	Sweden	Canada (5)	Canada (5)	France
6	Canada	Canada (6)	France (5)	France (5)	Sweden
7	Sweden	France (6)	Sweden	Germany (5)	Canada (7)
8	Germany	Germany	Germany	Sweden	Germany (7)
9	Japan	Japan	Japan	Japan	Japan
10	Australia	Australia	Australia	Australia	Australia
11	Italy	Italy	Italy	Italy	Italy
12	Spain	Spain	Spain	Spain	Spain

Source: Compiled by Science-Metrix from data prepared by ISI Thomson.

Canada has made some progress during the 12-year period: whereas it was in 6th place during the 1991-1993 and 1994-1996 periods, it moved to 5th rank in the 1997-1999 period (ex-equo with France) and finished in 5th place in the 2000-2002 period (ex-equo with France and Germany). Clearly, the pressure on Canada is very high on various fronts. Italy might overtake Canada in absolute number of publications soon. The United States is very close to Canada in terms of papers per capita and may overtake it easily due to much higher expenditures by the U.S.'s National Institutes of Health in genomics compared to the meagre grants given by the Canadian Institute of Health Research (see Figure 4) in this field – only 2% of NIH grants. Despite the financial support provided by Genome Canada, due to the preponderant share of the papers in genomics stemming from biomedical sciences, it is clear that the United States has an edge over Canada and is in a better position to increase scientific output. Canada is improving its index of specialization, but Australia and the United Kingdom are not far behind. Australia is experiencing a faster rate of growth in terms of its scientific output and may reach a higher rank than Canada in terms of its index of specialization in the near future.

Canada ranks highly in terms of impact factor, but France is increasingly publishing in journals that are highly cited which means that Canada may rank below France in the future. In terms of citations effectively received by Canada, it is threatened by Australia, which is regularly increasing the quality of its scientific output, and France may prove a strong competitor in the future too. Thus, the data presented in this section reveals that, globally, Canada is an important producer of scientific output in genomics at the world level and that its production is of a high standard. However, the multiple indicators used here converge, and one can see that Canada's position in the world of genome research is by no means guaranteed.

Canada has to increase its output whilst maintaining and even improving scientific excellence, which is clearly a big challenge for the years ahead. Since it is difficult to increase quantity and

quality simultaneously, it seems that Canada should prioritize quality since it cannot really compete in the long run with larger countries in terms of number of papers.

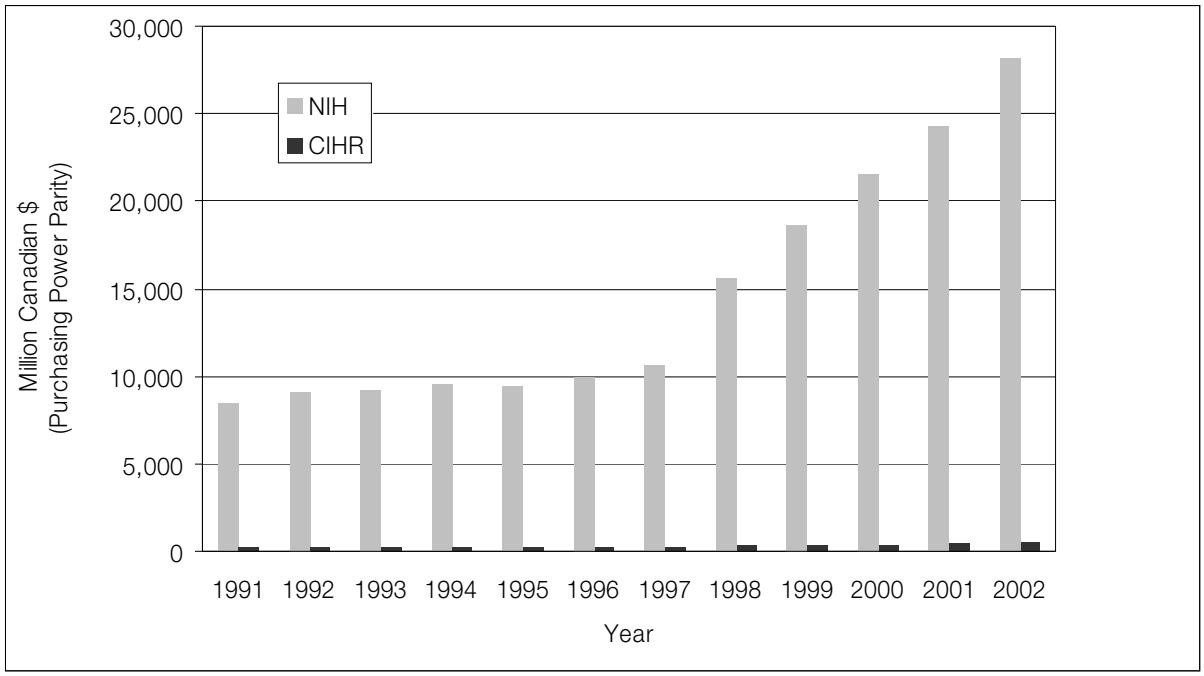


Figure 4 Grants by the NIH and the CIHR in million Canadian dollars at purchasing power parity, 1991-2002

Source: Compiled by Science-Metrix from various sources.

1.3# Benchmarking Canada by specialties in genomics

This section employs a multicriteria method to determine Canada's fields of excellence in genomics. Starting from a list of more than 100 fields and sub-fields, the specialties in which Canada published at least two papers per year on average during the last six years (1997-2002) and in which it ranks 6th or better are compiled in Table XII.

Starting with biomedical research, which is the most important field in terms of the number of papers published in genomics (170,911 papers published at the world level and 8,533 in Canada), Canada ranked 6th for the six-year period in question. Canada is well-positioned in the two most important specialties within biomedical medicine, that is, biochemistry and molecular biology and genetics and heredity, ranking 4th in both. Canada is also strong in cellular biology, cytology and histology (4th) and even more so in physiology (2nd).

Clinical medicine is the second most important field in genomics in terms of scientific output and Canada ranks 9th here. Neurology is the third specialty in terms of papers (after cancer research and immunology, two fields where Canada does not rank 6th or better), and it is also an area of excellence for Canada, since it ranks 3rd here. Canada is also a leader in endocrinology (2nd) and in pharmacology (4th). Although these specialties are not that important within the field of clinical medicine, it is noteworthy that Canada ranks 1st in fertility, respiratory systems and allergy.

The third field of importance in genomics is biology. Canada ranks 1st in marine biology and hydrology and 2nd in dairy and animal science and general zoology.

Finally, although this is a marginal field in genomics, it is noteworthy that Canada is a leader in earth and space where it ranks 1st, and, within this field, Canada also ranks 1st in the environmental science sub-field. Canada leads neither in engineering and technology nor in physics.

Table XII Multicriteria ranking of Canada within genomic fields, 1997-2002

Field	Papers		Rank					
	World	Canada	1	2	3	4	5	6
Biomedical Research	**170,911**	**8,533**	**U.S.**	**France**	**Switzerland**	**U.K.**	**Canada**	**Germany (6)**
Biochem & Molec Biol	67,182	3,151	U.S.	Switzerland	France	Canada	Germany (5)	U.K. (5)
Genetics & Heredity	40,004	2,443	Netherlands (1)	U.K. (1)	U.S.	Canada (4)	France (4)	Sweden
Genrl Biomedical Res	15,206	599	U.S.	U.K.	Switzerland	Canada (4)	France (4)	Germany (4)
Cell Biol Cyt & Hist	8,177	403	U.S.	Switzerland	Germany	Canada	U.K.	France
Physiology	3,545	244	U.S.	Canada	U.K.	Switzerland	Australia	Germany
Nutrition & Dietet	889	39	U.S.	Canada	Spain	U.K.	France	Japan
Biophysics	627	18	U.S.	France	Sweden	Germany	Canada	Italy
Clinical Medicine	**126,466**	**5,614**	**U.S.**	**Netherlands**	**Switzerland**	**Italy (4)**	**U.K. (4)**	**Japan**
Neurol & Neurosurg	18,132	1,019	U.S.	Switzerland	Canada	Germany	Sweden	U.K.
Pharmacology	9,236	449	U.K. (1)	U.S. (1)	France	Canada	Japan	Switzerland
Endocrinology	9,194	602	Sweden	Canada	U.S.	France	U.K.	Japan
Genrl & Internal Med	5,934	249	Netherlands (1)	U.K. (1)	U.S.	Switzerland	Canada	Sweden
Cardiovascular Systm	4,734	230	U.S.	Netherlands	Germany	Italy	Japan	Canada (6)
Fertility	2,036	139	Canada	U.S.	Australia	Netherlands	U.K.	Italy
Surgery	1,660	54	U.S.	Japan	Switzerland	U.K.	Germany	Canada
Obstetrics & Gynecol	1,328	57	U.K.	U.S.	Netherlands	Canada	Italy	Germany (6)
Pediatrics	1,276	60	Germany (1)	Netherlands (1)	Sweden	U.S.	U.K.	Canada
Urology	1,168	40	U.S.	Canada	Japan (3)	Sweden (3)	Germany	Netherlands
Radiology & Nucl Med	1,116	64	U.S.	Canada	Germany	Netherlands	U.K.	Japan
Psychiatry	1,082	81	U.K.	U.S.	Canada	Germany (4)	Sweden (4)	Italy
Dentistry	981	31	U.S.	Japan	U.K.	Australia	Sweden	Canada
Respiratory System	939	76	Canada	U.K.	Netherlands	U.S.	France (5)	Spain (5)
Envir & Occup Hlth	784	32	U.S.	U.K.	Netherlands	Sweden	Canada	France
Allergy	662	51	Canada	Netherlands	Sweden	Switzerland	U.K.	Australia
Misc Clinical Med	373	13	U.S.	Sweden	Australia	U.K.	Italy	Canada (6)
Orthopedics	330	22	U.S.	Canada	Japan	Australia	U.K.	Switzerland
Biology	**25,568**	**1,364**	**U.K.**	**Netherlands**	**Australia (3)**	**Japan (3)**	**U.S.**	**France (6)**
Biology	3,447	144	Australia	Japan	Spain	U.K. (4)	U.S. (4)	Canada (6)
Marine Bio & Hydrobi	2,184	191	Canada	Australia	U.S.	France	Japan (5)	U.K. (5)
Dairy & Animal Sci	1,896	146	Netherlands	Canada	U.S.	Germany	France	Sweden (6)
Entomology	1,605	77	U.S.	Australia (2)	France (2)	U.K.	Canada (5)	Germany (5)
General Zoology	1,182	75	Australia	Canada (2)	U.S. (2)	Sweden (4)	U.K. (4)	Japan
Ecology	557	40	Switzerland	U.K.	U.S.	Australia	Canada (5)	France (5)
Misc Zoology	455	20	U.S.	Sweden	France	Canada	Australia	U.K.
Chemistry	**7,942**	**224**	**Switzerland (1)**	**U.S. (1)**	**Sweden**	**Germany**	**France**	**Japan**
Chemistry	1,540	63	U.S.	Canada	Switzerland	Italy	Germany	Spain
Earth & Space	**736**	**50**	**Canada**	**Australia**	**U.S.**	**Netherlands**	**U.K.**	**France**
Environmental Sci	488	39	Canada	Australia (2)	Netherlands (2)	U.S. (2)	Spain	France
Engineering & Tech	**552**	**20**	**U.K.**	**Germany (2)**	**Italy (2)**	**Japan (2)**	**U.S.**	**Australia**
Physics	**1,056**	**21**	**Italy**	**Germany (2)**	**U.S. (2)**	**France**	**Spain (5)**	**Sweden (5)**

Source: Compiled by Science-Metrix from data prepared by ISI Thomson.

1.4# International collaboration by Canada in genomics

Canada has a well-developed network of international collaboration. In fact, the number of papers written in international collaboration is much higher than the number of papers written in inter-provincial collaboration. In fact, the percentage of international collaboration has risen steadily from 35% of papers during the 1991-1993 period to 46% during the 2000-2002 period (Table XIII).

Table XIII Main countries that collaborate with Canada in genomics, 1991-2002

Country	1991-1993	1994-1996	1997-1999	2000-2002	1991-2002
United States	1,381	1,867	2,154	2,240	7,642
United Kingdom	202	297	377	423	1,299
France	219	318	354	354	1,245
Germany	125	224	275	308	932
Japan	95	176	235	264	770
Netherlands	79	111	140	115	445
Australia	55	97	130	134	416
Italy	49	100	109	133	391
Sweden	54	91	104	118	367
Switzerland	49	65	95	98	307
Belgium	26	40	68	86	220
Spain	24	29	61	67	181
China	13	15	31	91	150
Denmark	27	22	45	54	148
Finland	18	28	38	64	148
Israel	22	24	47	55	148
Brazil	9	27	38	57	131
Austria	19	28	24	42	113
Norway	11	18	34	43	106
Greece	12	15	24	35	86
Russian Federation	13	25	19	28	85
New Zealand	16	14	18	30	78
Republic of Korea	4	3	19	41	67
Mexico	7	11	24	23	65
Poland	14	8	19	19	60
Taiwan	6	15	17	22	60
Collaborations	2,062	2,928	3,475	3,629	12,094
Total Papers	5,862	7,483	7,967	7,866	29,178
% in collaboration	35%	39%	44%	46%	41%

Source: Compiled by Science-Metrix from data prepared by ISI Thomson.

Canada's largest collaborator by far in genomics is the United States – it accounts for 63% of the papers written in collaboration. Next are the United Kingdom and France: Canadian scientists write about 10% of their collaborative papers with either of these countries. Germany and Japan are also important players with respectively 8% and 6% of Canadian collaborations. The Netherlands, Australia, Italy, Sweden and Switzerland are all collaborators of intermediate importance, each accounting for about 3% of Canadian collaborations in genomics.

Table XIV shows the main institutions that collaborate with Canada in each of the leading countries that were used to benchmark Canada's performance. It is noteworthy that this list is by no means extensive for any given country. For instance, there are several U.S. institutions not listed here that collaborate more with Canada than those listed for other countries. It is also noteworthy that the level of collaboration of some U.S. institutions is higher than that of whole countries despite the fact that each of these countries is a leader in genomics.

Not surprisingly, most of the collaborators are universities but there are also a number of national research institutions such as the National Cancer Institute in the U.S., CNRS, INSERM and INRA in France, CSIRO in Australia, CNR in Italy, and CSIC in Spain. With the exception of the Necker Hospital in France and the Karolinska Hospital in Sweden, few hospitals make it to the list of Canada's core collaborative partners. As for companies, Novartis stands out since it is the only company that makes it to the list of main collaborators for these countries.

The single largest collaborator is Harvard University (which accounts for 6.7% of U.S. collaborations in genomics with Canada) and is followed by the University of Washington. CNRS is a large collaborator but cannot be considered as a single entity since it encompasses laboratories from all around France in a very large variety of institutional settings.

Table XIV Main institutions that collaborate with Canada in genomics, 1991-2002

Institution	Number of papers in collaboration	% of country collaboration
United States	**7,642**	**100.0%**
Harvard University	510	6.7%
University of Washington	337	4.4%
National Cancer Institute	254	3.3%
Univ. of California at San Fransisco	221	2.9%
University of Pennsylvania	221	2.9%
University of Minnesota	202	2.6%
University of California, Los Angeles	199	2.6%
Washington University	199	2.6%
Baylor College of Medicine	198	2.6%
Johns Hopkins University	197	2.6%
University of Michigan	194	2.5%
Stanford University	187	2.4%
University of California, San Diego	175	2.3%
MIT	156	2.0%
University of Wisconsin, Madison	156	2.0%
Yale University	156	2.0%
Duke University	149	1.9%
University of California, Davis	145	1.9%
Cornell University	143	1.9%
Univ. of North Carolina at Chapel Hill	141	1.8%
United Kingdom	**1,299**	**100.0%**
University of London	213	16.4%
University of Cambridge	152	11.7%
University of Oxford	128	9.9%
University of Edinburgh	70	5.4%
Imperial Cancer Research Fund	58	4.5%
University of Leeds	55	4.2%
University of Manchester	46	3.5%
Medical Research Council	43	3.3%
John Radcliffe Hospital	39	3.0%
University of Birmingham	35	2.7%
France	**1,245**	**100.0%**
Institut Pasteur	81	6.5%
Hôpital de la Pitié-Salpêtrière	67	5.4%
Institut Curie	62	5.0%
Int. Agency for Research on Cancer	52	4.2%
Hôpital Necker - Enfants Malades	50	4.0%
Université de Rouen	37	3.0%
Univ. Louis Pasteur (Strasbourg I)	36	2.9%
Univ. Pierre et Marie Curie (Paris VI)	36	2.9%
Université Paris-Sud (Paris XI)	33	2.7%
Université Claude Bernard (Lyon I)	32	2.6%
Université Denis Diderot (Paris VII)	32	2.6%
CNRS	*451*	*36.2%*
INSERM	*310*	*24.9%*
INRA	*141*	*11.3%*
Germany	**932**	**100.0%**
Univ.München/Univ. of Munich	63	6.8%
Univ. Hamburg/Univ. of Hamburg	52	5.6%
Univ. Freiburg/Univ. of Freiburg	48	5.2%
Univ. Würzburg/Univ. of Wurzburg	47	5.0%
Univ. Bonn/Univ. Bonn	43	4.6%

Institution	Number of papers in collaboration	% of country collaborations
Japan	**770**	**100.0%**
University of Tokyo	80	10.4%
Osaka University	61	7.9%
Kyoto University	47	6.1%
Hokkaido University	39	5.1%
Kyushu University	36	4.7%
Netherlands	**445**	**100.0%**
Universiteit Leiden/Univ. of Leiden	70	15.7%
Erasmus Univ. Rotterdam	61	13.7%
Universiteit Van Amsterdam	59	13.3%
Universiteit Utrecht/Utrecht Univ.	56	12.6%
Free Univ. of Amsterdam	53	11.9%
Australia	**416**	**100.0%**
University of Melbourne	70	16.8%
University of Queensland	50	12.0%
CSIRO	45	10.8%
Monash University	37	8.9%
University of Adelaide	37	8.9%
University of Sydney	37	8.9%
Italy	**391**	**100.0%**
Univ. degli Studi di Torino/Univ. of Turin	46	11.8%
Univ. degli Studi di Milano/Univ. of Milan	38	9.7%
CNR	33	8.4%
Univ. degli Studi di Padova/Univ. of Padua	33	8.4%
Univ. degli Studi di Firenze/Univ.of Florence	28	7.2%
Univ. degli Studi di Roma "La Sapienza"/ Univ. of Rome "La Sapienza"	28	7.2%
Sweden	**367**	**100.0%**
Karolinska Institutet/Karolinska Institute	93	25.3%
Karolinska Sjukhuset/Karolinska Hospital	54	14.7%
Göteborgs Universitet/Gothenburg Univ.	50	13.6%
Lunds Universitet/Lund University	45	12.3%
Umeå Universitet/Umeå University	45	12.3%
Uppsala Universitet/Uppsala University	45	12.3%
Switzerland	**307**	**100.0%**
Universität Zürich/University of Zurich	75	24.4%
Université de Genève/Univ. of Geneva	59	19.2%
Universität Bern/University of Bern	40	13.0%
Novartis	39	12.7%
Eidgenössische Tech. Hochschule Zürich/ Swiss Federal Institute of Techn. Zurich	32	10.4%
Spain	**181**	**100.0%**
CSIC	47	26.0%
Universitat de Barcelona	22	12.2%
Universidad Autònoma de Madrid	19	10.5%
Universidad Complutense Madrid	13	7.2%
Universidad de Oviedo	8	4.4%

Source: Compiled by Science-Metrix from data prepared by ISI Thomson.

2#Genome Science at the Canadian Level

This section examines global trends in Canadian genomics, the distribution of papers among Canadian provinces and leading institutions and, lastly, the pattern of inter-provincial and inter-institutional collaboration networks between 1991 and 2002.

2.1# Global trends in Canadian genome science

Figure 5 shows that the number of Canadian papers in genomics grew steadily until 1996 after which they reached a steady level with more than 2,500 papers published every year. The number of scientific papers grew from about 1,700 in 1991 to 2,600 in 2001, an increase of more than 50% over the twelve-year period. In terms of the percentage of Canadian papers relative to total papers in genomics indexed in the SCI Expanded database, Canada produced an average of about 5% of all papers until 1999, after which it began to exhibit a small downward tendency.

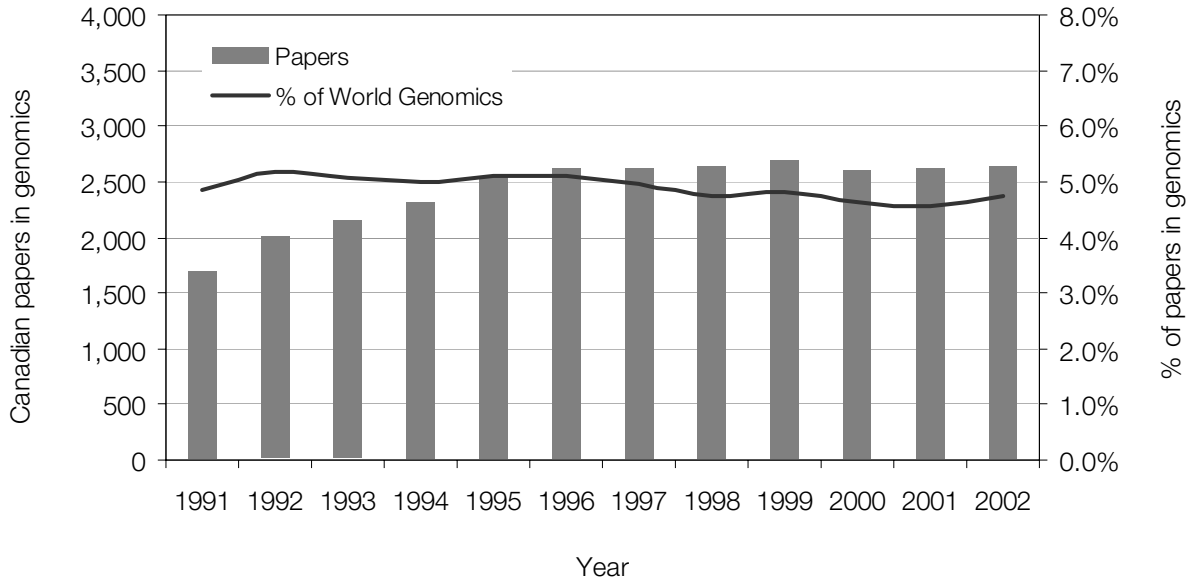


Figure 5 Canadian papers in genomics per year, 1991-2002
Source: Compiled by Science-Metrix from data prepared by ISI Thomson.

2.2# Genomic papers by province

Ontario and Quebec are the leaders in genomics in Canada but, similar to Canada as a whole, both provinces experienced flat growth between the last three-year periods. In fact, only Saskatchewan significantly increased its number of papers in genomics, and Alberta experienced a small increase in scientific output. Nova Scotia is the only Atlantic province with a sizeable output in genomics, although its output of the last twelve years is equivalent to that of Alberta during the last three years.

Table XV Papers in genomics by Canadian provinces, 1991-2002

Province	1991-1993	1994-1996	1997-1999	2000-2002	1991-2002
Ontario	2,477	3,131	3,330	3,280	12,218
Quebec	1,605	2,312	2,443	2,277	8,637
British Columbia	730	903	1,012	1,088	3,733
Alberta	737	860	934	986	3,517
Manitoba	240	300	287	299	1,126
Saskatchewan	188	228	260	328	1,004
Nova Scotia	204	216	285	259	964
Newfoundland	97	76	77	58	308
New Brunswick	31	40	61	52	184
P.E.I	10	25	21	28	84
Other & unknown	2	1	5	4	12
Canada	5,862	7,483	7,967	7,866	29,178

Source: Compiled by Science-Metrix from data prepared by ISI Thomson.

2.3# Genomic papers by leading Canadian institutions

Table XVI lists the 50 most active institutions in genomic science in terms of number of papers between 1991 and 2002. The top ranking institution during that period was the University of Toronto with 4,570 publications, thus accounting for approximately 16% of Canadian research papers in this field. Moreover, the biomedical research system network of university-affiliated hospitals (e.g. the Hospital for Sick Children with 1,336 papers in genomics, the University Health Network with 658 papers and the Mount Sinai Hospital of Toronto with 652 papers) makes the University of Toronto the core of the most important research network in genomics in Canada during that period.

McGill University ranked second with 3,739 publications. With 12.8% of Canadian genomics papers, McGill University and its affiliated hospitals (e.g. McGill University Health Centre with 721 papers and Sir Mortimer B. Davis - Jewish General Hospital with 316 papers) is at the core of the second most important Canadian research network in terms of output.

In third place is the University of British Columbia with 2,504 papers (8.6% of Canadian papers in genomics), followed by the University of Alberta with 1,981 papers (6.8%). Figuring in the top ten institutions, *Université Laval* (5th; 5.2%) and *Université de Montréal* (6th; 5.2%) performed well with more than 1,500 papers in the studied period. Their affiliated hospitals, *Centre hospitalier universitaire de Québec* (CHUQ), *Centre hospitalier universitaire de Montréal* (CHUM) and the *Centre hospitalier universitaire mère-enfant* (*Hôpital Sainte-Justine*), also appeared in the top 50 ranking, thus revealing the important role that these two university research networks play in knowledge production in genomics in Canada.

Other higher education establishments also had a noteworthy output in genomics: the University of Calgary (1,252 papers; 4.3% of the Canadian output), the University of Guelph (1,250 papers; 4.3%), McMaster University (1,116 papers; 3.8%), and the University of Western Ontario (1,029 papers; 3.5%).

Three federal government departments are also included in the table: Agriculture and Agri-Food Canada (ranking 12th with 1,026 publications), the Natural Research Council Canada (ranking 13th with 731 publications) and Natural Resources Canada (ranking 36th with 214 publications).

Table XVI Ranking of Canadian leading institutions in genomics in terms of number of papers, share of total Canadian papers in genomics, and number and percentage of papers in collaboration,1991-2002

Rank	Institution	Papers in genomics	% of Canadian papers in genomics	Collaborations
1	University of Toronto	4,570	15.7%	2,557
2	McGill University	3,739	12.8%	1,697
3	University of British Columbia	2,504	8.6%	935
4	University of Alberta	1,981	6.8%	548
5	Université Laval	1,527	5.2%	792
6	Université de Montréal	1,503	5.2%	736
7	The Hospital for Sick Children	1,336	4.6%	998
8	University of Calgary	1,252	4.3%	376
9	University of Guelph	1,250	4.3%	317
10	McMaster University	1,116	3.8%	385
11	University of Western Ontario	1,029	3.5%	423
12	Agriculture and Agri-food Canada	1,026	3.5%	444
13	Ottawa University	920	3.2%	525
14	University of Manitoba	911	3.1%	326
15	Queen's University	771	2.6%	250
16	Dalhousie University	768	2.6%	245
17	National Research Council Canada	731	2.5%	394
18	Centre hospitalier universitaire de Québec (CHUQ)	722	2.5%	548
19	McGill University Health Centre (MUHC)	721	2.5%	592
20	University of Saskatchewan	714	2.4%	225
21	University Health Network	658	2.3%	558
22	Mount Sinai Hospital of Toronto	652	2.2%	536
23	British Columbia Ministry of Health Services	422	1.4%	270
24	Université de Sherbrooke	384	1.3%	96
25	University of Victoria	366	1.3%	105
26	Sir Mortimer B Davis-Jewish Hospital	316	1.1%	272
27	Institut de recherches cliniques de Montréal (IRCM)	309	1.1%	178
28	York University	282	1.0%	84
29	Memorial University of Newfoundland	269	0.9%	114
30	Simon Fraser University	264	0.9%	97
31	Institut national de la recherche scientifique (INRS)	225	0.8%	87
32	Health Canada	223	0.8%	126
33	Department of Fisheries and Oceans Canada	218	0.7%	113
34	Centre hospitalier de l'Université de Mtl (CHUM)	216	0.7%	149
35	Centre hospitalier universitaire mère-enfant	214	0.7%	168
36	Natural Resources Canada	214	0.7%	112
37	Cancer Care Ontario	211	0.7%	176
38	University of Waterloo	194	0.7%	62
39	Vancouver Coastal Health Authority	174	0.6%	140
40	Ontario Cancer Institute	173	0.6%	128
41	Sunnybrook & Womens College Health Sci Ctre	169	0.6%	151
42	Alberta Cross Cancer Institute	165	0.6%	105
43	London Health Sciences Centre	154	0.5%	122
44	Carleton University	139	0.5%	64
45	Concordia University	138	0.5%	39
46	Ottawa Hospital	131	0.4%	113
47	Children's Hospital of Eastern Ontario	129	0.4%	100
48	Children's & Women's Health Centre of B.C. (C&W)	128	0.4%	95
49	Université du Québec à Montréal (UQAM)	125	0.4%	70
50	Alberta Children's Hospital (ACH)	111	0.4%	93
	Canada	29,178	100.0%	9,193

Source: Compiled by Science-Metrix from data prepared by ISI Thomson.

2.4# Collaboration in genomics in Canada

Inter-provincial collaborations are somewhat marginal in Canadian genomics. Less than 10% of the papers in genomics are by Canadian scientists from different provinces. This contrasts with the more than 40% of papers being written with international collaborators. Despite this, one can still observe a growth, albeit a slow one, since the rate of inter-provincial collaborations rose by about 22% between 1991 and 2002. The rise in inter-institutional collaborations has been fairly steady during the last twelve years: the rate of collaboration grew by nearly 30% between 1991 and 2002.

Table XVII shows that scientists from smaller provinces have a greater propensity to collaborate with those of other provinces. The rate of collaboration is lowest in Quebec and in Ontario (respectively 12% and 14%), whereas Prince Edward Island and Newfoundland have the highest propensity to collaborate with other provinces (respectively 42% and 37% of their papers).

Ontario and Quebec have the largest rate of bilateral collaboration. Ontario has an important collaboration with British Columbia and Alberta; the two provinces are also involved in a substantial amount of collaboration with Quebec. Proximity and size, however, do not explain everything. For example, Nova Scotia collaborates nearly as frequently with Ontario as Manitoba does. One can suspect that collaboration between federal government laboratories is at play here.

Table XVII Collaboration by Canadian provinces, 1991-2002

Province	Ontario	Quebec	Alberta	British Columbia	Manitoba	Nova Scotia	Saskatchewan	Newfoundland	New Brunswick	Prince Edward Island	Northwest Territories
Ontario		739	323	341	147	133	87	68	23	25	2
Quebec	739		136	136	52	72	42	21	6	6	
Alberta	323	136		102	66	25	75	14	9	4	6
British Columbia	341	136	102		43	42	30	19	13	2	
Manitoba	147	52	66	43		9	36	9	2	3	
Nova Scotia	133	72	25	42	9		2	13	13	2	
Saskatchewan	87	42	75	30	36	2		5		2	1
Newfoundland	68	21	14	19	9	13	5		4		
New Brunswick	23	6	9	13	2	13		4		2	
Prince Edward Island	25	6	4	2	3	2	2		2		
Northwest Territories	2		6				1				
Collaborations	**1,685**	**1,058**	**644**	**617**	**291**	**244**	**232**	**115**	**59**	**35**	**6**
Total Papers	12,218	8,637	3,517	3,733	1,126	964	1,004	308	184	84	9
% Collaboration	14%	12%	18%	17%	26%	25%	23%	37%	32%	42%	67%

Source: Compiled by Science-Metrix from data prepared by ISI Thomson.

The inter-institutional collaboration matrix presented in Table XVIII shows, not surprisingly, that the most frequent collaborations are between the large Canadian universities and their affiliated hospitals. For instance, McGill collaborates frequently with the MUHC, whereas the University of

Toronto collaborates with the Hospital for Sick Children, the Mount Sinai Hospital and the University Health Network. The largest inter-institutional collaborations outside the traditional university-hospital relationship are between McGill and the Université de Montréal (279 papers), between McGill and the University of Toronto (136 papers), between McGill and the National Research Council of Canada (85 papers) and, lastly, between the University of Toronto and the University of British Columbia (74 papers).

As one may expect, leading Canadian institutions in genomics collaborate more frequently with other research institutions located in the same geographical area.

Table XVIII Canadian genomics: inter-institutional collaboration matrix, 1991-2002

Institution	University of Toronto	McGill University	University of British Columbia	University of Alberta	Université Laval	Université de Montréal	The Hospital for Sick Children	University of Calgary	University of Guelph	McMaster University	University of Western Ontario	Agriculture and Agri-food Canada	Ottawa University	University of Manitoba	Queen's University	Dalhousie University	National Research Council Canada	Ctre hospitalier univ. de Québec (CHUQ)	McGill University Health Centre (MUHC)	University of Saskatchewan	University Health Network	Mount Sinai Hospital of Toronto
University of Toronto		136	74	46	21	38	833	28	31	68	68	16	32	35	48	31	15	11	37	3	468	482
McGill University	136		43	42	61	279	62	23	8	20	19	49	56	19	27	23	85	43	526	6	17	17
University of British Columbia	74	43		30	18	11	30	16	11	9	27	37	13	21	15	18	18	5	11	6	6	3
University of Alberta	46	42	30		5	8	18	76	11	28	18	35	13	23	12	8	21	4	10	22	6	5
Université Laval	21	61	18	5		49	7	11	9	6	4	38	4	4	6	14	4	468	12	3		4
Université de Montréal	38	279	11	8	49		7	9	4	8	3	14	18	7	1	21	21	28	49	6	7	4
The Hospital for Sick Children	833	62	30	18	7	7		9	11	30	7	2	5	7	29	9	1	6	28		86	59
University of Calgary	28	23	16	76	11	9	9		7	8	14	14	7	18	12	7	9	3	4	21	2	2
University of Guelph	31	8	11	11	9	4	11	7		17	5	57	3	5	8	9	13	1		13	13	2
McMaster University	68	20	9	28	6	8	30	8	17		15	7	12	8	22	11	2	1	3	7	19	10
University of Western Ontario	68	19	27	18	4	3	7	14	5	15		12	10	15	4	8	3	2	6	1	8	14
Agriculture and Agri-food Canada	16	49	37	35	38	14	2	14	57	7	12		30	25	9	2	17			28	2	1
Ottawa University	32	56	13	13	4	18	5	7	3	12	10	30		6	6	24	34	2	21	6	7	4
University of Manitoba	35	19	21	23	4	7	7	18	5	8	15	25	6		3	4	4	2	1	5	6	5
Queen's University	48	27	15	12	6	1	29	12	8	22	4	9	6	3		2	4	1	9	4	5	10
Dalhousie University	31	23	18	8	14	21	9	7	9	11	8	2	24	4	2		23	1	3	1	3	6
National Research Council Canada	15	85	18	21	4	21	1	9	13	2	3	17	34	4	4	23			14	52	3	4
Ctre hospitalier univ. de Québec (CHUQ)	11	43	5	4	468	28	6	3	1	1	2		2	2	1	1			12		1	3
McGill University Health Centre (MUHC)	37	526	11	10	12	49	28	4		3	6		21	1	9	3	14	12		1	10	1
University of Saskatchewan	3	6	6	22	3	6		21	13	7	1	28	6	5	4	1	52		1		2	1
University Health Network	468	17	6	6		7	86	2	13	19	8	2	7	6	5	3	3	1	10	2		67
Mount Sinai Hospital of Toronto	482	17	3	5	4	4	59	2	2	10	14	1	4	5	10	6	4	3	1	1	67	
Collaborations	2,557	1,697	935	548	792	736	998	376	317	385	423	444	525	326	250	245	394	548	592	225	558	536
Total papers	4,570	3,739	2,504	1,981	1,527	1,503	1,336	1,252	1,250	1,116	1,029	1,026	920	911	771	768	731	722	721	714	658	652
% Collaboration	56%	45%	37%	28%	52%	49%	75%	30%	25%	34%	41%	43%	57%	36%	32%	32%	54%	76%	82%	32%	85%	82%

Source: Compiled by Science-Metrix from data prepared by ISI Thomson.

PART II
TECHNOLOGICAL INVENTIONS IN GENOMICS

3# TechnologicalInventions in Genomics

This section examines the distribution of patents granted by the United States Patent and Trademark Office (USPTO) at the international level. In particular, Section 3.1 examines the rate of growth of patents in genomics, Section 3.2 examines the distribution of patents by country, and Section 3.3 examines the distribution of patents by Canadian province.

3.1#Intellectual property in genomics at the international level and in Canada

Between 1991 and 2002, the number of patents granted by the USPTO in genomics grew by more than sixfold, increasing from 713 to 4,592. The percentage of genomic patents relative to the total number of patents granted by the USPTO also grew considerably, increasing from 0.7% to 2.5%. In Figure 6, one can see a pattern similar to the one observed for scientific papers: in 1998 the number of patents in genomics reached what appears to be a stable state with 4,000 to 5,000 patents being granted each year.

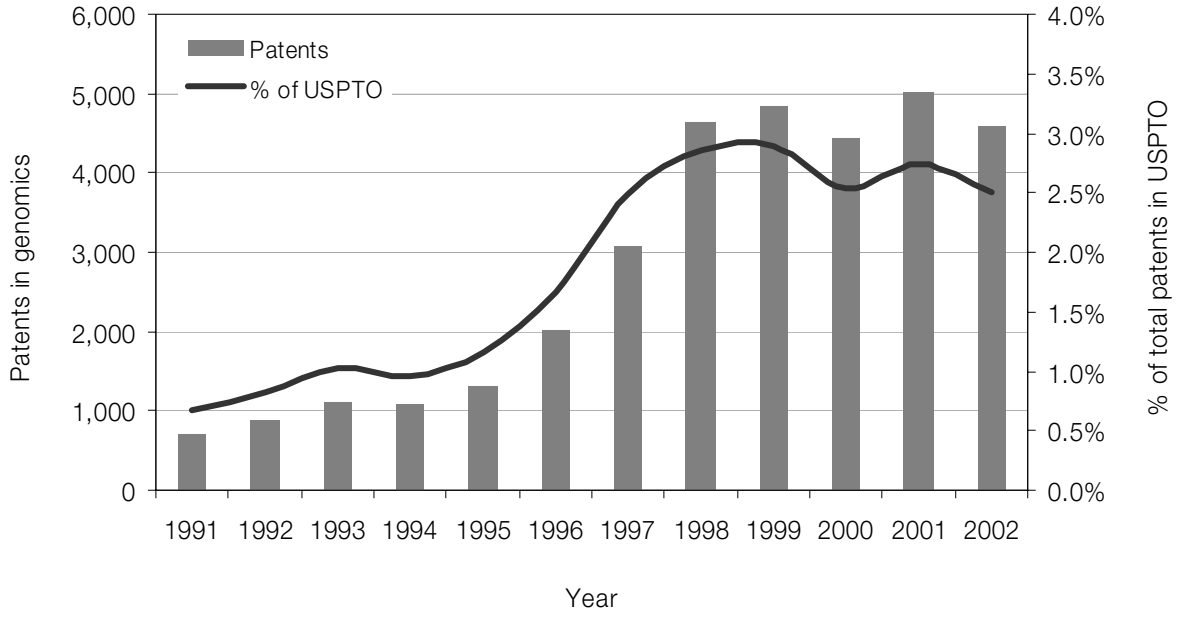


Figure 6 Patents in genomics granted by the USPTO, 1991-2002
Source: Compiled by Science-Metrix from USPTO data.

Figure 7 shows that Canada is an important player in the field of genomic inventions. It has nearly as many patents as countries that are much larger have (Germany, the United Kingdom and France). Together with the U.S. and Japan, Canada is by far the most important producer of IP in the field of genomics. Figure 8 shows that Canada has had one of the highest growth rates in patents.

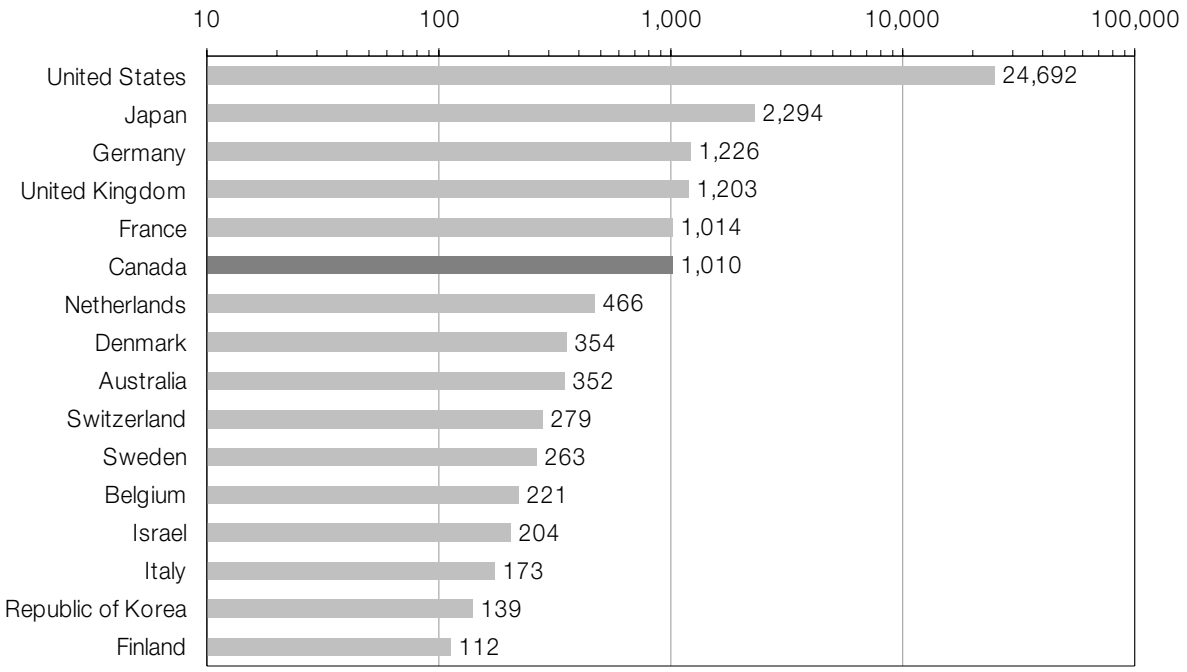


Figure 7 Patents in genomics by leading countries, 1991-2002
Source: Compiled by Science-Metrix from USPTO data.

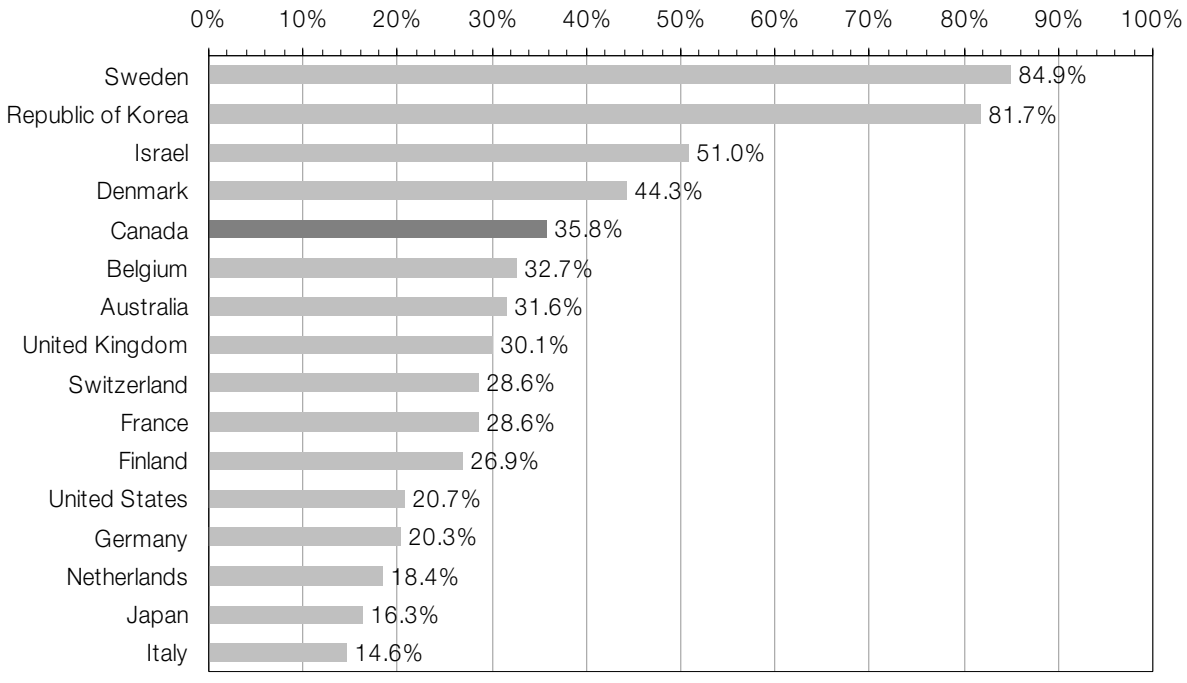


Figure 8 Average yearly growth of patents by leading countries, 1991-2002
Source: Compiled by Science-Metrix from USPTO data.

Yet, as shown in Figure 9, the number of patents obtained by Canada in genomics follow a similar pattern to that of the whole field, as shown previously (Figure 6). Hence Canada's high growth rate, as observed in Figure 8, is a feature of the past.

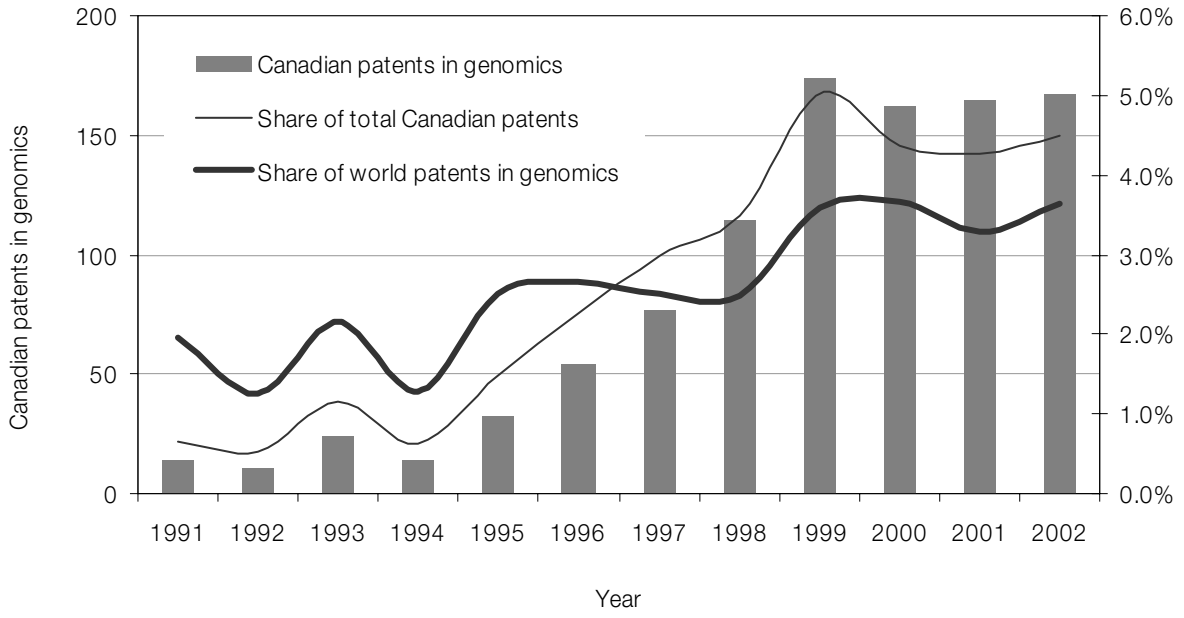


Figure 9 Canadian patents in genomics granted by the USPTO, 1991-2002
Source: Compiled by Science-Metrix from USPTO data.

3.2# Benchmarking Canada in genome technology

This section follows the same method as that used to benchmark Canada in genome science. The section successively examines the number of patents granted, the patents per capita, the index of specialization and the number of citations per patent and then combines these metrics in a multicriteria benchmark.

3.2.1# Number of patents in genomics granted by the USPTO

Table XIX shows that Canada and France are head-to-head in terms of intellectual property protection in genomics. In fact, as mentioned before, Germany, the United Kingdom, France and Canada are in the same league in terms of the number of patents. Canada patents more than twice as many patents as its next competitor (the Netherlands), which means that its position is not really threatened in the short term, despite a slow-down in the number of patents it has obtained. Overall, Canada occupies the 5th and 6th ranks over the period in close competition with France (Table XX).

Table XIX Number of patents by leading countries in genomics, 1991-2002

Country	1991-1993	1994-1996	1997-1999	2000-2002	1991-2002
United States	2,020	3,245	9,270	10,157	24,692
Japan	255	407	820	812	2,294
Germany	105	154	421	546	1,226
United Kingdom	48	131	426	598	1,203
France	60	97	400	457	1,014
Canada	49	101	366	494	1,010
Netherlands	41	57	189	179	466
Australia	19	54	126	153	352
Switzerland	14	33	88	144	279
Sweden	19	32	88	124	263
Italy	25	34	63	51	173
Spain	5	6	15	24	50
World	2,713	4,421	12,557	14,051	33,742

Source: Compiled by Science-Metrix from USPTO data.

Table XX Ranking of leading countries according to the number of patents in genomics, 1991-2002

Rank	1991-1993	1994-1996	1997-1999	2000-2002	1991-2002
1	U.S.	U.S.	U.S.	U.S.	U.S.
2	Japan	Japan	Japan	Japan	Japan
3	Germany	Germany	U.K.	U.K.	Germany
4	France	U.K.	Germany	Germany	U.K.
5	Canada	Canada	France	Canada	France
6	U.K.	France	Canada	France	Canada
7	Netherlands	Netherlands	Netherlands	Netherlands	Netherlands
8	Italy	Australia	Australia	Australia	Australia
9	Australia (9)	Italy	Sweden (9)	Switzerland	Switzerland
10	Sweden (9)	Switzerland	Switzerland (9)	Sweden	Sweden
11	Switzerland	Sweden	Italy	Italy	Italy
12	Spain	Spain	Spain	Spain	Spain

Source: Compiled by Science-Metrix from USPTO data.

3.2.2# Number of patents per capita

Canada occupies the third rank in terms of patents per capita in genomics. It is preceded only by the U.S., which is hardly surprising, and by Switzerland (Table XXI). The Netherlands and Sweden follow Canada in a close race, especially in the case of Sweden, which demonstrates a very important increase in patents per capita for every one of the periods.

Table XXI Number of patents per million inhabitants by leading countries in genomics, 1991-2002

Country	1991-1993	1994-1996	1997-1999	2000-2002	1991-2002
United States	2.62	4.05	11.18	11.88	7.59
Switzerland	0.67	1.53	4.06	6.59	3.24
Canada	0.57	1.13	3.97	5.21	2.80
Netherlands	0.90	1.23	4.01	3.74	2.49
Sweden	0.73	1.21	3.31	4.66	2.49
United Kingdom	0.28	0.75	2.40	3.34	1.71
Australia	0.36	0.99	2.23	2.63	1.59
Japan	0.68	1.08	2.16	2.13	1.52
France	0.35	0.56	2.26	2.55	1.44
Germany	0.43	0.63	1.71	2.21	1.25
Italy	0.15	0.20	0.36	0.29	0.25
Spain	0.04	0.05	0.13	0.20	0.10
World	0.17	0.26	0.71	0.76	0.48

Source: Compiled by Science-Metrix from USPTO data.

Table XXII shows that Canada's rate of growth in patents per capita helped it improve its relative position, starting at 6th place in 1991-1993 and progressively climbing to 3rd place in 2000-2002.

Table XXII Ranking of leading countries according to the number of patents per capita in genomics, 1991-2002

Rank	1991-1993	1994-1996	1997-1999	2000-2002	1991-2002
1	U.S.	U.S.	U.S.	U.S.	U.S.
2	Netherlands	Switzerland	Switzerland	Switzerland	Switzerland
3	Sweden	Netherlands	Netherlands	Canada	Canada
4	Japan	Sweden	Canada	Sweden	Netherlands
5	Switzerland	Canada	Sweden	Netherlands	Sweden
6	Canada	Japan	U.K.	U.K.	U.K.
7	Germany	Australia	France	Australia	Australia
8	Australia	U.K.	Australia	France	Japan
9	France	Germany	Japan	Germany	France
10	U.K.	France	Germany	Japan	Germany
11	Italy	Italy	Italy	Italy	Italy
12	Spain	Spain	Spain	Spain	Spain

Source: Compiled by Science-Metrix from USPTO data.

3.2.3# Index of specialization

Canada is fourth in terms of the index of specialization in intellectual property in genomics. It is preceded by Australia, the Netherlands and the United Kingdom (Table XXIII). Germany and Japan, two countries that have a strong tradition in protecting their inventions with patents, do not have such a high propensity to obtain patents in genomics.

Table XXIII Index of specialization of patenting in genomics, 1991-2002

Country	1991-1993	1994-1996	1997-1999	2000-2002	1991-2002
Australia	1.62	2.71	2.22	2.22	2.26
Netherlands	2.28	2.03	2.52	1.65	2.05
United Kingdom	0.83	1.68	1.89	2.54	1.97
Canada	0.93	1.16	1.42	1.68	1.48
United States	1.30	1.24	1.27	1.30	1.28
France	0.79	0.93	1.39	1.42	1.25
Spain	1.32	1.07	0.86	1.26	1.09
Sweden	1.04	0.97	0.82	0.83	0.90
Switzerland	0.42	0.67	0.71	0.96	0.76
Germany	0.59	0.61	0.60	0.64	0.61
Italy	0.77	0.77	0.53	0.39	0.51
Japan	0.44	0.45	0.33	0.30	0.34
World	1.00	1.00	1.00	1.00	1.00

Source: Compiled by Science-Metrix from USPTO data.

Canada's position in terms of the index of specialization is very similar to that observed for patents per capita, that is, it followed a staggered progression from 6th to 3rd position during the four

reference periods observed here (Table XXIV). The U.K. has made even more important progress, which now places it in top place, followed by Australia.

Table XXIV Ranking of leading countries according to the index of specialization in patenting in genomics, 1991-2002

Rank	1991-1993	1994-1996	1997-1999	2000-2002	1991-2002
1	Netherlands	Australia	Netherlands	U.K.	Australia
2	Australia	Netherlands	Australia	Australia	Netherlands
3	Spain	U.K.	U.K.	Canada	U.K.
4	U.S.	U.S.	Canada	Netherlands	Canada
5	Sweden	Canada	France	France	U.S.
6	Canada	Spain	U.S.	U.S.	France
7	U.K.	Sweden	Spain	Spain	Spain
8	France	France	Sweden	Switzerland	Sweden
9	Italy	Italy	Switzerland	Sweden	Switzerland
10	Germany	Switzerland	Germany	Germany	Germany
11	Japan	Germany	Italy	Italy	Italy
12	Switzerland	Japan	Japan	Japan	Japan

Source: Compiled by Science-Metrix from USPTO data.

3.2.4# Average relative citation

Citations received for Canadian patents show not only that Canada has many patents in genomics but also that they appear to have a substantial impact on the field's technological evolution (Table XXV).

Table XXV Average relative citations per patent for leading countries in genomics, 1991-2002

Country	1991-1993	1994-1996	1997-1999	2000-2002	1991-2002
United States	1.11	1.10	1.11	1.13	1.12
Netherlands	0.84	1.62	0.76	0.92	0.98
Spain	0.38	0.45	1.00	1.67	0.96
Sweden	0.80	0.92	0.85	1.21	0.92
Canada	0.89	1.06	0.94	0.91	0.89
United Kingdom	0.71	0.55	0.94	0.89	0.80
Switzerland	1.36	0.61	0.82	0.53	0.67
France	0.41	0.48	0.68	0.82	0.65
Germany	0.80	0.68	0.69	0.54	0.64
Japan	0.62	0.66	0.54	0.53	0.61
Australia	1.00	0.40	0.48	0.33	0.45
Italy	0.23	0.31	0.45	0.07	0.35
World	1.00	1.00	1.00	1.00	1.00

Source: Compiled by Science-Metrix from USPTO data.

Canada is fifth overall but as Table XXVI shows, it has already ranked 4th and even 3rd in this respect. It is closely followed by the U.K. in terms of citations per patent. The big surprise here is Spain, which ranked 2nd in 1997-1999 and 1st in 2000-2002.

Table XXVI Ranking of leading countries according to average relative citations per patent, 1991-2002

Rank	1991-1993	1994-1996	1997-1999	2000-2002	1991-2002
1	Switzerland	Netherlands	U.S.	Spain	U.S.
2	U.S.	U.S.	Spain	Sweden	Netherlands
3	Australia	Canada	U.K.	U.S.	Spain
4	Canada	Sweden	Canada	Netherlands	Sweden
5	Netherlands	Germany	Sweden	Canada	Canada
6	Sweden	Japan	Switzerland	U.K.	U.K.
7	Germany	Switzerland	Netherlands	France	Switzerland
8	U.K.	U.K.	Germany	Germany	France
9	Japan	France	France	Switzerland	Germany
10	France	Spain	Japan	Japan	Japan
11	Spain	Australia	Australia	Australia	Australia
12	Italy	Italy	Italy	Italy	Italy

Source: Compiled by Science-Metrix from USPTO data.

3.2.5# Multicriteria analysis

The last part in the benchmarking of Canada in genomic technology is to globally evaluate how it ranks compared to other leading countries. Using four criteria, Canada ranked 3rd during the first three periods and 2nd during the last three-year period. With the United Kingdom being increasingly competitive in genomics patents, Canada might return to the 3rd rank in the next three-year period (Table XXVII).

Table XXVII Multicriteria ranking of patents by leading countries in genomics, 1991-2002

Rank	1991-1993	1994-1996	1997-1999	2000-2002	1991-2002
1	U.S.	U.S.	U.S.	U.S.	U.S.
2	Netherlands	Netherlands	U.K.	Canada (2)	Netherlands
3	Canada	Canada	Canada (3)	U.K. (2)	Canada
4	Australia	U.K.	Netherlands (3)	Netherlands	U.K.
5	Sweden	Japan (5)	France (5)	Sweden	Australia (5)
6	Japan	Sweden (5)	Switzerland (5)	France	Sweden (5)
7	Germany	Australia	Sweden	Australia (7)	Switzerland (5)
8	Switzerland	Germany	Australia	Switzerland (7)	France
9	France (9)	Switzerland	Germany	Germany	Germany (9)
10	U.K. (9)	France	Japan (10)	Spain	Japan (9)
11	Spain	Spain	Spain (10)	Japan	Spain
12	Italy	Italy	Italy	Italy	Italy

Source: Compiled by Science-Metrix from USPTO data.

3.3# Inventions in genomics by Canadian provinces

This last section examines the distribution of patents within Canada. Ontario has a huge advance over Quebec, which in turn has an important advance over Alberta and British Columbia (Table XXVIII). In fact, Ontario's advance over Quebec is proportionately more important in terms of patents than it is in terms of scientific publications. The Atlantic Provinces and Manitoba are not really party to the technological race. Importantly, the growth in patents is largely due to Ontario and Quebec's performance; a number of other provinces are even experiencing a decline.

Table XXVIII Number of patents by province in Canada, 1991-2002

Province	1991-1993	1994-1996	1997-1999	2000-2002	1991-2002
Ontario	24	49	170	248	491
Quebec	15	22	77	110	224
Alberta	2	11	37	39	89
British Columbia	5	4	36	30	75
Saskatchewan	2	9	26	16	53
Manitoba	1	1	7	5	14
Nova Scotia	-	-	2	4	6
Newfoundland	-	1	-	-	1
Unknown	1	6	24	49	80
Canada	49	101	366	494	1,010

Source: Compiled by Science-Metrix from USPTO data.

Conclusion

Canada has consistently improved its position in world genomic science during the last ten years. However, this is not yet a success story and it is certainly not a good time to give up investments in this field. For example, back in the 1960s and 1970s, Canada was an important player in an emerging field – microelectronics. Canada had good science, it had sound technology. Today, Canadians are nearly nowhere to be seen in this sector: *"Unlike countries such as Taiwan or the USA, in Canada there are no facilities aimed at fabricating high-volume, general-purpose devices, such as memory components and microprocessors"*[8]. Genomics is now where microelectronics was some thirty years ago, entering its phase of maturity where developments are not only occurring in the laboratory, but actually starting to shape the economic landscape for real. In microelectronics, Canada never leveraged its strengths as much as it could have done. In genomics, Canadians should be aware of their strengths, of the potential developments of years to come and of their truly tangible capability to not only have an important impact on the field and but also reap some important benefits, both economically and socially.

This report shows that the field of genomics has reached its cruising speed at the Canadian as well as at the world level both in terms of science as well as in terms of technology. Production has reached the top level of the S-shaped curve that is often observed in natural as well as in social systems. This suggests that genomics has entered its "adult life", that it is no longer an emerging field but rather that it has become an established discipline. Hence, we can only come to the same conclusion as the U.S. National Human Genome Research Institute, i.e. that the "genomic era is now a reality"[9]. According to this organisation, the forthcoming challenge of transferring the knowledge generated in the field of genomics is threefold:

- Genomics to biology – Elucidating the structure and function of genomes.
- Genomics to health – Translating genome-based knowledge into health benefits.
- Genomics to society – Promoting the use of genomics to maximize benefits and minimize harms.

This report shows that Canada is well positioned to undertake these challenges from a scientific and from a technological point-of-view. The share of the scientific output published by Canada is 5% of the world output in genomics. Nevertheless, the scientific output by Canadian genomicists is stable and most countries are actually experiencing a faster growth rate. In practical terms, this means that Canada faces the prospect of being overtaken by latecomers in the field. Importantly though, Canada's science is of high quality.

Since it is difficult to simultaneously increase the quantity and the quality of scientific papers, two seemingly contradictory targets, Canada has to make a choice and the choice to make appears to be a clear one. Even if Canada substantially increases its output, it will not overtake the science of the

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[8] Canadian Microelectronics Corporation (1999). *Integrating Research & Growth, 2000-2005*. Chapter 5.4.

[9] Collins, F.S. *et al.* (2003) A vision for the future of genomics research. *Nature*. (422): 835.

larger countries and may not even be able to hold its own against fast-growing countries such as Spain and Italy – to say nothing of the longer-term threat posed by the Republic of Korea and China. The mode to favour clearly is an increase in the quality of Canada's scientific production. To achieve this goal, it is suggested to encourage researchers to aim for excellence and to develop international collaboration with the best research centres and the best researchers in the field.

The really positive news is that Canada has an excellent intellectual property position given its relative size. The indicators on patents converge to reveal that Canada is in the leading pack: it ranks 3rd overall and even managed to rank 2nd during the most recent three-year period. This is an indicator that Canada's output in genomics has an intrinsic economic value. Indeed, when venture capitalists invest in a project, the availability of patents is always factored in and highly valued. Furthermore, patents are also an indicator of potential value since many of these inventions are yet to be transformed into commercially viable products and processes and have therefore not completely realized their value. Finally, it also shows that in genomics, Canadian practitioners are pragmatic and looking forward to commercially exploiting their findings.

The future of Canadian genomics looks bright. The science has reached its cruising speed and the technology has important potential for commercial applications. If Canada plays its cards carefully, it could end up enjoying a position similar to that it currently occupies in biotechnology – that is – not being a giant but being able to play at the same table as the most important players in the field.