Australian Science
Performance from published papers

Report 96/3

January 1996

Australian Government Publishing Service
Canberra

ISBN 0 644

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Printed in Australia by

Foreword

In 1995, the BIE undertook to benchmark the Australian science and technology system. As in all our international benchmarking studies, the major objective of the project was to learn how we compare with leading nations and, perhaps, how to do things better. By having a few well understood indicators, we will be better able to monitor our progress. The science benchmarking project involves identifying quantitative and qualitative indicators of outputs, inputs and science capabilities. This is one of three reports associated with the project. The first, *Science Awareness and Understanding* (June 1995), dealt with the Australian public's understanding and awareness of science. The second, *Science System: International benchmarking* (January 1996), is the major report of the project. This, the third, deals in more detail with the performance of codified scientific research as measured by papers and citations.

In producing this report we are indebted to Paul Bourke and Linda Butler of the Research School of Social Sciences at the Australian National University for the provision of data, insights and comments on a draft. Dr Lyn Grigg provided some additional useful insights. We also wish to thank David Pendlebury of the Institute of Scientific Information, whose ISI database form the backbone of this study. We also extend our thanks to the Department of Industry, Science and Technology's S&T counsellors – Dr Mike Fitzpatrick (London), Daryl Back (Washington) and Don Smale (Japan) – who provided valuable data for this report.

The report was prepared by Ralph Lattimore and John Revesz with some research assistance from Samantha Welsh. John Houghton was an internal referee and provided very useful comments as did Barbara Martin.

January 1996

Bob Hawkins
Director

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Abbreviations

BIE	Bureau of Industry Economics
ISI	Institute of Scientific Information
S&T	Science and technology
RCA	Revealed comparative advantage
NSF	National Science Foundation
ASRC	Australian Standard Research Classification

Summary

This publication accompanies the BIE's benchmarking report on science (BIE 1996). In this report, we use data on scientific papers and citations to look at the performance of Australian academic science relative to other countries. Scientific papers only measure one part of a science system, but they suggest something of the quality, productivity and breadth of basic scientific research.

Australia's relative performance

Australian science produced 180 000 papers from 1981 to 1994 or 2.1 per cent of science papers in the world. By world standing this is a large contribution. Australia is ranked tenth in the world in our absolute contribution to scientific papers.

® Australia produces 25 per cent more than Sweden, 50 per cent more than Switzerland, twice as much as China, five times more than Taiwan and nearly nine times more than South Korea.

Australian scientific papers are widely cited relative to most countries:

® citations per paper provide a measure of the visibility and, to some extent, quality of academic scientific research. Australia has higher average citation rates than Germany, France, Italy and Japan. Australia has the third highest citation rate among APEC countries (behind the US and Canada).

Australia has particular excellence in fields close to our rich natural endowments, with high relative citation rates for papers in agriculture, ecology and the environment, geoscience and plant and animals science.

Australia has broad scientific capabilities as measured by the shares of papers across 20 scientific fields. Australian science is less broad than the US, Canada and the major European economies, but broader than Sweden, Norway and Japan. Broadness increases the technological and scientific options available to a country – which is important when it is hard to foresee new scientific developments.

Australia has highly *consistent* quality in scientific publications across fields – more so than the UK, Netherlands and France (ie quality does not vary too much across fields).

Australia contributes more to published science than its income or population would suggest. For example, Australian scientists publish 60 per cent more papers than would be normally expected given our income.

International links

Australia has strong and rapidly growing academic linkages with other countries. Over one fifth of Australia's higher education scientific papers were co-authored with a foreign scientist – a near doubling of the proportion since 1981.

Europe and North America are still the most important sites for collaboration. From 1981 to 1992, nearly 80 per cent of Australia's academic collaborative papers were with the US, Canada, the UK and Europe. Over the last decade, Europe has grown in prominence while the UK has declined. We also found particularly strong growth in collaboration with Asia, and particularly Japan and China. Interestingly, there was negligible growth in the already weak levels of scientific academic collaboration with either Taiwan or South Korea – two of the most dynamic of the emerging scientifically developed countries in the region.

Dynamic performance

At 3.6 per cent per annum over the last 14 years, Australia's growth in papers has been roughly on par with world trends. However, much of this growth occurred since 1988 – so that Australia's share of world's most prominent scientific publications grew during the last six years.

But the picture suggested by citation rates is more complex. Citation rates rose slowly from the early 1980s before plateauing in the late 1980s. In contrast, world citation rates continued to grow, so that Australia's *relative* citation impact has been falling (with a particularly abrupt downturn since the late 1980s).

The fields experiencing the biggest reductions in relative citation impact were immunology, chemistry, materials science and microbiology. In contrast, fields such as engineering, mathematics, astrophysics and multidisciplinary science increased their relative citation impact over the last decade.

It is hard to interpret these falling relative citation impacts. We find that:

® Australia's case is not exceptional. Countries like Denmark, Norway and Sweden have faced similar reductions. Nor is it the case that the newly industrialised countries are overtaking us: both Taiwan and South Korea also faced reductions of the same order as Australia (albeit they expanded their share of world publications dramatically at the same time).

® There have been other periods (such as the mid 1970s) when Australia's relative citation impacts have fallen – only to recover later.

® All countries have some fields which have been declining. Indeed we find that the 'average' country has nine fields out of twenty experiencing such a decline. But Australia is distinctive in that so many (15 of 20) scientific fields have exhibited a trend decline in relative citation impacts from 1981-85 to 1990-94.

The report examines a wide range of reasons which might underlie the general decline in impact. Some of the pattern of falling relative citation rates appears to be due to convergence by countries with poorer systems. We also found evidence that two factors are positively correlated with citation rates – R&D spending per head of population (especially on higher education), and published papers per researcher. The former has risen in Australia in recent years, while the latter has fallen – with the second effect dominating.

The report considered a range of other possible factors, such as dilution of resources for the best scientists, structural change in science, poorer access to networks, ageing of scientists, a weakening in the quality of our scientists, and data errors. In some cases, such as ageing and structural change, these are unlikely to underlie the decline. For most of the others, there was insufficient evidence to come to a clear-cut conclusion.

1. Introduction

1.1 Introduction

In 1993 *Science Watch*, a journal produced by the Institute of Scientific Information (ISI) in the US, revealed a recent decline in the impact of Australian scientific publications. This study was followed by Bourke and Butlers' (1994) elaborate and careful examination of data based on scientific papers. They found a decline in Australia's share of world citations, and a relatively stable share of world publications. We re-assess this issue in this report by looking closely at the Australian data, making detailed comparisons with other countries and trying to discover some of the causes of the patterns that we find.

But our interest in these data extends beyond this re-assessment. We use the publication data to examine other aspects of the Australian science system, such as structural change, its relative standing in the region, and the extent to which Australian scientists are establishing linkages with other countries. This report is a companion volume to BIE (1996) which makes a detailed assessment of how the Australian science system is performing relative to other countries.

1.2 Background

Since 1991 the BIE has conducted a comprehensive set of benchmarking studies of infrastructure services. These have included electricity, telecommunications and gas, among others. More recently we have extended benchmarking to less tangible infrastructure, including Australia's science and technology system (S&T). In this report we present results on the performance of Australia's science system using data on scientific papers, while in BIE (1996) we present an overall appraisal of the system.

1.3 Why codified knowledge matters

Many of the major benefits of a science system occur through tacit transfers of knowledge and skill transfers rather than through codified knowledge, such as patents or scientific papers. Nevertheless, codified knowledge in the form of published scientific literature remains important. It:

- provides valuable knowledge to institutions or firms with enough scientific capacity to absorb it;
- is accessible to many users and can be disseminated easily and cheaply;
- provides a permanent store of knowledge that can be exploited years after its production;
- provides pointers to key research and to important practitioners of science – whether they are institutions or individual researchers; and
- certifies the origin of ideas, which is important in determining status and promotion within the institutions producing research outputs.

It is therefore worthwhile measuring the magnitude, productivity, and impact of such scientific codified knowledge. This is the subject of this report. We use statistical analysis of publications and citations – so-called bibliometrics – to do this.

1.4 The database

The Institute for Scientific Information (ISI) in Philadelphia has produced a major statistical database on scientific papers and citations for about 80 countries and more than 4000 journals for the years 1981 to 1994.[1] The countries included are those which published 1000 or more papers[2] in science journals indexed by the ISI over this period, while the journals cover the most influential peer reviewed scientific journals. The records of papers and citations have been divided into 20 fields of science.[3]

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[1] We thank David Pendlebury of ISI for assistance with the ISI database and for permission to publish the results in this chapter. The ISI country listing needed to be adapted for our purposes. The list includes some double counting (for example it incorporates Wales, Scotland, Northern Ireland and England as well as the UK). For recent years it also incorporates some new countries such as the Ukraine, Russia and the other new states formed after the collapse of the Soviet Union, while maintaining listing of the USSR for past years. Since many benchmark measures (such as ranking) make little sense if there are changes in the countries, we maintained a constant country list through time by ignoring these changes in boundaries and by excluding any double counted countries. Altogether that left 79 countries.

[2] Papers are defined as articles, notes, reviews and proceedings papers but not editorials, letters, corrections or abstracts. A paper is attributed to a country so long as one of the authors was addressed to that country. For this reason, the sum of papers across countries is higher than the total number of papers produced.

[3] The ISI database actually covers some additional social science disciplines, but we have excluded these fields from our analysis. At this level of aggregation, the ISI classification of fields vary from those of the Australian Standard Research Classification (ASRC).

There are many different ways in which the database can be used to indicate the output and impact of scientific papers, running from absolute counts of citations and papers to comparisons of citations per paper between countries and fields.

The ISI database has limitations (appendix A). It does not include all codified forms of knowledge, such as books, conference papers, working papers, and Internet notes. Nor does it cover all significant scientific journals – many Australian journals are not included. Nor are journals from non-English speaking countries as well represented as those from English speaking countries. Nevertheless:

- coverage is still high for most fields; and
- many of these deficiencies are irrelevant if the purpose is to compare relative performance *over time*. A bias would only be produced if Australian journals were increasingly under or over-represented compared to other countries.

We emphasise that when we make ‘world’ comparisons using the ISI database, some parts of the world are less represented in the journal set than is desirable.

1.5 Organisation of the report

In chapter 2 we take a snapshot of Australia’s performance in scientific papers and citations relative to the world. We explore our strengths and weaknesses by scientific field – and make an overall assessment of Australia’s scientific proclivity.

In chapter 3 we examine the pattern of collaboration with other countries – to see the extent and focus of academic scientific collaborative publishing.

In chapter 4 we turn to Australia’s performance over time. In particular, we critically examine whether and why Australian scientific papers are being cited less often relative to the world.

We interpret and summarise the overall results in chapter 5.

2 A snapshot of Australia's performance

2.1 The results for total publications

Over the period from 1981-1994 Australia produced about 180 000 papers[1] or 2.1 per cent of science papers in the world (table 2.1).

While this is small in absolute terms, it is far larger than many other countries. Australia produces 10 per cent more than the Netherlands, 25 per cent more than Sweden, 50 per cent more than Switzerland, more than twice as much as China, five times more than Taiwan, and nearly nine times more than South Korea. Australia is ranked fourth (behind the US, Japan and Canada) in its production of scientific papers among the 18 countries of APEC.

Counts of papers suffer some limitations as a measure of codified knowledge. In particular, a superb and path breaking paper is given the same weight as a mediocre one. One method of adjusting for quality differences is to look at citations rather than papers. This method also suffers from limitations:

- Scientists find it costly to search all journals for high quality articles relevant to a given scientific field. Researchers will often reduce these search costs by using (and citing) articles in the most prominent journals and by the most prominent scientists. This suggests, for example, that citation rates of an excellent article by a researcher with a known reputation published in a well known journal will be higher than that of an equally excellent paper by a relatively unknown researcher in a less well known journal.

- Papers which describe technical methods may be cited thousands of times, while path breaking papers which are ahead of the times may be cited relatively slightly for many years. For example, in chemistry most of the highly cited publications are simple trade recipes, analytical methods in biochemistry and manipulative techniques rather than profound science (NBEET 1993, p.60).

[1] Note that this relates only to peer reviewed papers in the journals covered by the ISI. The total would be higher if other journals were included.

- Papers published in English will tend to be cited more frequently than non-English papers.

Table 2.1 Papers and citations, 1981 to 1994 [a]

	Papers	*Rank*	*Citations*	*Rank*	*Papers cited at least once*	*Rank*	*Share of world papers*	*Share of world citations*	*Share of world cited papers*
Australia	180,133	(10)	1,484,804	(9)	136,477	(9)	0.021	0.021	0.023
Canada	376,588	(7)	3,222,103	(5)	283,573	(6)	0.045	0.045	0.048
Chile	13,780	(38)	64,902	(34)	8,604	(37)	0.002	0.001	0.001
Denmark	71,025	(19)	705,579	(14)	55,355	(17)	0.008	0.010	0.009
Finland	56,870	(21)	438,978	(18)	41,926	(19)	0.007	0.006	0.007
France	434,218	(6)	3,204,053	(6)	299,306	(5)	0.052	0.045	0.050
Germany	593,503	(3)	4,341,845	(3)	406,123	(4)	0.070	0.060	0.068
Hong Kong	12,964	(39)	56,064	(36)	8,241	(38)	0.002	0.001	0.001
India	205,195	(9)	467,570	(17)	107,667	(12)	0.024	0.007	0.018
Indonesia	2,142	(61)	8,610	(58)	1,312	(59)	0.000	0.000	0.000
Italy	228,901	(8)	1,473,742	(10)	159,292	(8)	0.027	0.021	0.027
Japan	613,114	(4)	4,080,152	(4)	437,791	(3)	0.073	0.057	0.074
Malaysia	4,632	(49)	13,918	(49)	2,736	(48)	0.001	0.000	0.000
Mexico	21,130	(34)	91,669	(32)	12,586	(34)	0.003	0.001	0.002
Netherlands	164,558	(11)	1,547,286	(7)	126,100	(10)	0.020	0.022	0.021
New Zealand	37,841	(27)	259,557	(22)	28,211	(25)	0.004	0.004	0.005
Norway	43,564	(25)	336,736	(19)	33,061	(23)	0.005	0.005	0.006
PNG	1,517	(71)	6,965	(62)	948	(71)	0.000	0.000	0.000
P.R. China	79,419	(17)	181,860	(24)	36,391	(20)	0.009	0.003	0.006
Philippines	3,307	(51)	16,328	(48)	2,090	(51)	0.000	0.000	0.000
Singapore	9,649	(43)	27,063	(47)	5,254	(44)	0.001	0.000	0.001
S. Africa	43,042	(24)	199,584	(23)	28,945	(24)	0.005	0.003	0.005
S. Korea	20,850	(36)	56,825	(35)	11,056	(35)	0.002	0.001	0.002
Sweden	143,261	(12)	1,510,356	(8)	111,795	(11)	0.017	0.021	0.019
Switzerland	119,094	(13)	1,396,597	(11)	88,243	(13)	0.014	0.019	0.015
Taiwan	34,091	(28)	101,375	(31)	18,746	(28)	0.004	0.001	0.003
Thailand	6,887	(46)	30,827	(43)	4,122	(46)	0.001	0.000	0.001
UK	671,944	(2)	6,560,169	(2)	509,185	(2)	0.080	0.091	0.086
US	2,919,889	(1)	35,248,880	(1)	2,254,415	(1)	0.346	0.490	0.380
Africa & M.E	182722		953782		116798		0.022	0.013	0.020
C&S America	90199		348291		53429		0.011	0.005	0.009
Rest of world	1,042,115		3,449,564		540,748		0.124	0.048	0.091
APEC	4,337,933		44,951,902		3,252,553		0.515	0.625	0.548
TOTAL	**8,428,144**		**71,886,034**		**5,930,526**		**1.000**	**1.000**	**1.000**

a Africa and M.E. is Africa and Middle Eastern states except S. Africa. C&S America is central and South America except Chile. APEC are the countries making up APEC except Brunei for which no information was available. Some journal articles are written by authors from different countries. Each of these is recorded as an article attributed to a country. Thus the total number of papers exceeds the real world total -but we use the inflated total so that any shares add to one. We did not use the full set of ISI fields in computing the above statistics. The following fields were excluded: Economics & business, Education, and Social Sciences. Accordingly, the above data will not match ISI totals. The rankings are among the 79 countries that make up our amended ISI database. No rankings are defined for regions (as in Africa and the Middle East, Central and South America and the Rest of the world) which are composed of many countries.

Source: ISI database, 1981-94.

- Review articles can mask citations of the articles they review. Once a review article covering a topic is published, other papers may quote from the review article rather than tracking back to the original research underpinning the review.

- Citation practices vary by scientific field. For example, citation rates in papers in molecular biology and genetics are far higher than those in materials science. We are reluctant to view the differences *between* scientific fields as indicative of differing quality standards. These large variations in citation rates between fields suggests a need to correct for the structure of scientific study in different countries, a point we return to later.

Nevertheless, we believe that the ISI database on citations provides a good measure of the visibility of Australian science and a possible guide to its overall quality. Australia commands just over 2 per cent of the total citations of papers in the world – with an average citation rate per paper[2] being just over eight (table 2.2). This citation rate places Australia in eighth ranking in the world – just behind Canada – but ahead of countries like Germany, France, Italy, and Japan. Australia has the third highest citation rate among APEC countries (behind the US and Canada) – and notably ahead of Japan.

But as we noted above, structural differences in the nature of scientific research in different countries may distort our perspective of Australia's standing. For example, imagine that there are just two scientific fields: astrophysics and agricultural science and only two countries. Both countries produce 1 100 papers, but country A produces mainly agricultural science papers, while country B produces mainly astrophysics (table 2.3).

Looked at from a disaggregated level, country A seems to produce superior quality papers. Citations per paper are higher for both fields. But because country A specialises in the production of agricultural science, a discipline whose practices and nature mean that citation rates are lower, the overall picture of citation rates suggests that country A has poorer quality science than country B.

One way of overcoming this measurement problem is to produce a weighted average of citations per paper using *fixed* weights for both countries. One sensible choice of weights is the world share of papers in each field (in this case 50 per cent).[3] This suggests that country A is clearly superior to B.

Table 2.2 Citation impacts, 1981 to 1994

	Share cited[a]	*Rank*	*Citation rate*[b]	*Rank*	*Relative impact*[c]	*Relative cited*[d]
Australia	0.76	(7)	8.24	(8)	0.97	1.08
Canada	0.75	(8)	8.56	(7)	1.00	1.07
Chile	0.62	(34)	4.71	(28)	0.55	0.89
Denmark	0.78	(2)	9.93	(4)	1.16	1.11

[2] Of those produced over the period from 1981-1994. The ISI has many other ways of recording citations. We look at these more closely in chapter 4.

[3] There are many other possible choices for weights. Two others are the weights facing country A or the weights facing country B. The critical thing is that the same weights be used for both countries.

Finland	0.74	(13)	7.72	(12)	0.90	1.05
France	0.69	(18)	7.38	(14)	0.87	0.98
Germany	0.68	(19)	7.32	(15)	0.86	0.97
Hong Kong	0.64	(29)	4.32	(36)	0.51	0.90
India	0.52	(62)	2.28	(66)	0.27	0.75
Indonesia	0.61	(38)	4.02	(40)	0.47	0.87
Italy	0.70	(17)	6.44	(19)	0.75	0.99
Japan	0.71	(14)	6.65	(18)	0.78	1.01
Malaysia	0.59	(47)	3.00	(53)	0.35	0.84
Mexico	0.60	(45)	4.34	(34)	0.51	0.85
Netherlands	0.77	(4)	9.40	(6)	1.10	1.09
New Zealand	0.75	(9)	6.86	(17)	0.80	1.06
Norway	0.76	(5)	7.73	(11)	0.91	1.08
PNG	0.62	(33)	4.59	(32)	0.54	0.89
P.R. China	0.46	(77)	2.29	(65)	0.27	0.65
Philippines	0.63	(31)	4.94	(27)	0.58	0.90
Singapore	0.54	(55)	2.80	(58)	0.33	0.77
S. Africa	0.67	(21)	4.64	(30)	0.54	0.96
S. Korea	0.53	(61)	2.73	(60)	0.32	0.75
Sweden	0.78	(1)	10.54	(3)	1.24	1.11
Switzerland	0.74	(11)	11.73	(2)	1.37	1.05
Taiwan	0.55	(53)	2.97	(54)	0.35	0.78
Thailand	0.60	(44)	4.48	(33)	0.52	0.85
UK	0.76	(6)	9.76	(5)	1.14	1.08
US	0.77	(3)	12.07	(1)	1.42	1.10
Africa & M. East	0.64		5.22		0.61	0.91
C&S America	0.59		3.86		0.45	0.84
Rest of world	0.52		3.31		0.39	0.74
APEC	0.75		10.36		1.21	1.07
TOTAL	**0.70**		**8.53**		**1.00**	**1.00**

a The share cited is the ratio of papers which are cited at least once to total papers. **b** Citation rate is the number of citations per paper. **c** Relative citation impact for the ith country is a country's share of world citations divided by its share of world publications. **d** Relative cited is the ratio of the proportion of papers which are cited at least once in a particular country relative to that of the world. See appendix B for formulas.

Source: ISI database, 1981-94.

Table 2.3 Hypothetical impact of structural differences on citation impact

		Country A	*Country B*	*World*
Papers produced	Agricultural science	1,000	100	1,100
	Astrophysics	100	1,000	1,100
	All fields	1,100	1,100	2,200
Citations	Agricultural science	4,000	300	4,300
	Astrophysics	1,300	12000	13,300
	All fields	5,300	12,300	17,600
Citations per paper	Agricultural science	4.0	3.0	3.9
	Astrophysics	13.0	12.0	12.1
	All fields	4.8	11.2	8.0
Weighted citation per paper		**8.5**	**7.5**	**8.0**

We re-adjusted the data for each country using this method. We found (table 2.4) that Australian relative citation impact scarcely changed. There were some substantial shifts in measured performance for some countries. Sweden, Switzerland and Denmark experience moderately large declines in performance (probably due to the relatively large proportion of research conducted in the highly cited field of medical science).

Relatively large increases in performance are apparent for China, Philippines and Taiwan.

Table 2.4 Citations per paper adjusted for science structure [a]

	Australian weights	*Rank*	*World weights*	*Rank*	*Unadjusted results*	*Rank*
Australia	8.24	(8)	8.22	(8)	8.24	(8)
Canada	8.62	(7)	8.71	(7)	8.56	(7)
Chile	4.18	(37)	4.14	(38)	4.71	(28)
Denmark	9.09	(5)	9.44	(5)	9.93	(4)
Finland	6.95	(15)	7.17	(14)	7.72	(12)
France	6.94	(16)	7.14	(15)	7.38	(14)
Germany	7.22	(12)	7.46	(11)	7.32	(15)
Hong Kong	4.33	(34)	4.38	(34)	4.32	(36)
India	2.52	(69)	2.64	(65)	2.28	(66)
Indonesia	4.16	(38)	3.94	(43)	4.02	(40)
Italy	5.84	(23)	6.07	(22)	6.44	(19)
Japan	6.26	(20)	6.44	(20)	6.65	(18)
Malaysia	3.18	(58)	3.12	(58)	3.00	(53)
Mexico	4.33	(35)	4.37	(35)	4.34	(34)
Netherlands	8.69	(6)	8.90	(6)	9.40	(6)
New Zealand	7.15	(13)	7.40	(12)	6.86	(17)
Norway	7.36	(11)	7.31	(13)	7.73	(11)
PNG	4.62	(31)	4.30	(36)	4.59	(32)
P.R. China	3.22	(57)	3.18	(57)	2.29	(65)
Philippines	6.49	(18)	6.52	(19)	4.94	(27)
Singapore	3.24	(55)	3.26	(54)	2.80	(58)
S. Africa	5.03	(27)	5.04	(27)	4.64	(30)
S. Korea	3.22	(56)	3.21	(55)	2.73	(60)
Sweden	9.54	(4)	9.61	(3)	10.54	(3)
Switzerland	10.42	(2)	10.83	(2)	11.73	(2)
Taiwan	3.58	(49)	3.59	(48)	2.97	(54)
Thailand	4.48	(32)	4.48	(33)	4.48	(33)
UK	9.54	(3)	9.52	(4)	9.76	(5)
US	11.66	(1)	11.92	(1)	12.07	(1)

a The Australian weights are the share of papers in a given field in Australia, the world weights are the share of papers in a given field in the world, while the unadjusted results use each country's own weights to calculate the overall citation rate. Note that for some countries (such as Thailand) there are some scientific fields where citation rates could not be calculated because no papers were produced in those fields. We simply used the unadjusted citation rate for those countries, when computing rankings (ie we did not actually adjust the data for these countries at all).

Source: BIE calculations based on the ISI database.

Australia's position in the league tables of science 'quality' does not alter after the adjustments for field structure (although the position of some other countries, like the Philippines, China, the UK and New Zealand, did shift).

Another measure of visibility and/or quality of research is whether a paper is cited at all. Over the period from 1981 to 1994, 76 per cent of scientific papers published by

Australians were cited at least once.[4] Australia is ranked seventh in the world and just behind the US in APEC countries on this measure.

2.2 Australia’s contribution by field of research

Four fields dominate Australian scientific publications: biology and biochemistry, clinical medicine, chemistry and plant and animal science. Together these account for 51.2 per cent of scientific papers produced by Australians from 1981 to 1994 (table 2.5). However, other than the prominent role of plant and animal science, this pattern is not extraordinary. Indeed, if Australia matched the rest of the world, a greater share of our papers would be produced in the first three fields. To put the Australian numbers in context we must turn to international comparisons.

It is worth drawing a distinction between three international measures of performance by field for a given country:

- a country’s share of total world papers or citations in that field. This is an indicator of the ‘raw’ scientific strength of a country by field of science;
- a country’s citation rate in a field relative to world citation rates in that field. This is an indicator of the quality and visibility of different fields of science; and
- the share of a country’s papers (or citations) in a given field *relative to* the share of the world’s papers (or citations) in that field. This is a measure of **revealed comparative advantage (RCA)** by scientific field. A country has a revealed comparative advantage in a field if the share of that country’s papers or citations in that field is much higher than the world share of papers or citations in that field.[5] Thus if the measure is well above one then a comparative advantage is

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[4] This figure should not be taken to imply that about one quarter of papers are never cited. The process of citation takes time. The data used to calculate the 76 per cent figure span fourteen years from 1981 to 1994. Papers published in 1994 have very little time to be cited, while those published in 1981 have had fourteen years. The ISI database records that 87 per cent of scientific papers published in 1981 by Australians were cited at least once by 1994, while only 16.5 per cent of papers published in 1994 were cited at least once.

[5] The premise underlying the use of this measure is that countries with a comparative advantage in a particular field devote proportionately more resources (and produce more outputs) to that field than other countries. More formally, the measure of comparative advantage we are using here is:

$$RCA_{i,j} = (P_{i,j} / \Sigma_{i=1}^{N} P_{i,j}) \Big/ \left(\Sigma_{j=1}^{k} P_{i,j} / \Sigma_{j=1}^{N} \Sigma_{j=1}^{k} P_{i,j}\right) = (P_{i,j} / \Sigma_{j=1}^{k} P_{i,j}) \Big/ \left(\Sigma_{i=1}^{N} P_{i,j} / \Sigma_{j=1}^{N} \Sigma_{j=1}^{k} P_{i,j}\right)$$

This shows that the measure of revealed comparative advantage can be thought of in two ways. It is a country’s share of total world papers in that field relative to that country’s share of total world papers in all fields and equivalently as the share of a country’s papers in a given field relative to the share of world papers in that field. We emphasise that the measure suffers some limitations as a measure of comparative advantage. After all, the allocation of resources in the science system is not determined in a purely competitive market – in much of the science system the allocation of funding is determined by federal and revealed, while if the measure is well below one then a comparative disadvantage is suggested.

Table 2.5 Papers and citations by field of science, 1981-1994

	Field share of Australian papers	*Field Share of Australian citations*	*Relative citation impact*	*Share of world papers*	*Share of world citations*	*Number of papers*	*Number of citations*	*Citation rate*
	% a	**% b**	**c**	**% d**	**% e**			**f**
Agricultural Sciences	4.9	2.7	1.22	3.9	4.8	8,845	40,022	4.52
Astrophysics	1.5	2.3	1.07	2.5	2.7	2,734	34,889	12.76
Biology & Biochemistry	12.3	18.5	0.90	2.0	1.8	22,138	274,246	12.39
Chemistry	8.9	9.5	1.24	1.5	1.9	16,065	140,523	8.75
Clinical Medicine	17.0	16.2	0.97	2.0	1.9	30,550	239,798	7.85
Computer Science	0.8	0.3	0.84	1.5	1.3	1,392	3,851	2.77
Ecology/Env't	3.3	2.6	1.12	3.6	4.1	5,923	38,483	6.50
Engineering	4.7	2.1	1.16	1.6	1.8	8,514	31,353	3.68
Geosciences	4.6	4.9	1.16	3.9	4.5	8,202	72,067	8.79
Immunology	2.7	4.7	0.86	2.9	2.5	4,810	70,419	14.64
Materials Science	1.9	0.9	1.10	1.4	1.6	3,459	13,756	3.98
Mathematics	1.9	0.9	1.05	2.2	2.4	3,390	12,790	3.77
Microbiology	2.7	3.6	0.86	2.6	2.2	4,930	53,689	10.89
Molec Biol & Genetics	3.1	5.7	0.73	2.3	1.7	5,660	84,751	14.97
Multidisciplinary	1.2	0.7	1.09	1.7	1.9	2,165	9,717	4.49
Neuroscience	3.2	5.0	0.87	2.1	1.8	5,830	74,155	12.72
Pharmacology	2.4	2.8	1.06	1.9	2.0	4,375	41,789	9.55
Physics	6.3	4.8	0.83	1.2	1.0	11,366	70,890	6.24
Plant & Animal Sc	13.0	9.5	1.21	4.0	4.9	23,330	140,339	6.02
Psychology/psychiatry	3.6	2.5	0.80	3.0	2.4	6,455	37,277	5.77
All fields	**100.0**	**100.0**	**0.97**	**2.1**	**2.1**	**180,133**	**1,484,804**	**8.24**

a This is the ratio of Australian papers in a given field to total Australian scientific papers. **b** This is the ratio of Australian citations in a given field to total Australian scientific citations. **c** The ratio of the share of world citations divided by the share of world publications for a given field. **d** The share of world papers by field. **e** The share of world citations by field. **f** The ratio of citations to papers in Australia for a given field.

Source: Data from the ISI database.

We looked at international scientific strength by field by ranking all countries from top to bottom in terms of shares of world citations. We prefer citation shares because they take account of both the volume of publications and to some extent their visibility and quality. The US clearly dominates the production of codified knowledge – producing from 37 to 70 per cent of world scientific citations, depending on the field (table C.3 in appendix C). No other country contributes more in any field – the US has an absolute advantage spanning *all* fields. But what about others in the top ten percent? We take the top eight performing countries in the world as demonstrating some clear advantage in a scientific field. Notwithstanding Australia's size, Australia is within the top eight of 79

state governments. They may not always devote resources to the areas with the greatest potential social returns. Even so, we think the measure does reveal Australia's broad comparative advantages.

countries in terms of citation shares for 10 of the 20 fields. Japan is within the top eight for 18 of the 20 fields, Canada for 19, Sweden for 6, Switzerland for 4, and India for one (table C.5 in appendix C). Other than Japan, Asian economies still rank relatively low in terms of their absolute contribution to world science.

One problem with publication or citation shares is that they may overlook small countries with very high quality publications. We calculated relative citation impacts by field and country – these measure the quality (and visibility) of the scientific research. Australia was ranked 8th in the world or better in nine of the twenty scientific fields. It is interesting to compare these results (table A2.3) with those obtained by looking at citation shares. The US and the UK dominate world science both in quantity and quality stakes, but Japan, France, Germany and Canada fall in their rankings when quality measures are considered. While Japan is a big world player in terms of the absolute number of publications and citations, its citation *rates* are relatively low. In fact, Japan does not make it to the top eight in *any* field using this measure. In contrast, some smaller countries, like Switzerland, Sweden and the Netherlands may contribute relatively little to the stock of codified knowledge, but what they do produce is highly cited.

We summarise the fields where Australia ranks highly in world terms in table 2.6. We have international strengths in ecology and the environmental sciences, geoscience, plant and animal science and psychology/psychiatry and to a lesser extent, agricultural science, astrophysics, engineering, materials science and mathematics.[6] These are our absolute strengths. What about our revealed comparative advantages?

Some fields have a far greater share of Australia's total published scientific papers than they do in the world's total papers. For example, agricultural science accounts for 4.9 per cent of Australian papers but only 2.67 per cent of world papers. This implies that it has a revealed comparative advantage index (RCAI) of 1.84. We found that the RCA index was high for other natural sciences too: ecology and the environment (1.69), geosciences (1.81) and plant and animal sciences (1.88). This pattern of specialisation is not accidental, but reflects Australia's economic advantages in using its natural resources.[7]

Table 2.6 Australia's world ranking by scientific field, 1981-1994 [a]

	World publication shares	*World citation shares*	*Relative citation impact*

[6] Some care must be used when interpreting these numbers. In one field, psychology/psychiatry, Australia has fewer citations per paper than the world average, yet ranks quite highly in world terms in terms of citation rates. This oddity reflects the fact that this discipline is dominated by a very few countries, particularly the US, Canada and the UK.

[7] A similar, even more stark, picture of our comparative advantage in these fields emerges when we look at Australia's share of world citations by field relative to our overall share of citations.

Agricultural Sciences	7	√	6	√	9	
Astrophysics	10		8	√	6	√
Biology & Biochemistry	11		11		10	
Chemistry	13		11		7	√
Clinical Medicine	11		10		13	
Computer Science	10		10		12	
Ecology/Env't	5	√	4	√	6	√
Engineering	10		8	√	5	√
Geosciences	7	√	5	√	4	√
Immunology	8	√	10		11	
Materials Science	11		8	√	7	√
Mathematics	9		8	√	7	√
Microbiology	9		8	√	10	
Molec Biol & Genetics	10		9		15	
Multidisciplinary	10		9		18	
Neuroscience	10		10		10	
Pharmacology	10		11		9	
Physics	15		16		18	
Plant & Animal Science	8	√	5	√	5	√
Psychology/psychiatry	5	√	4	√	7	√

a The rankings are based on Australia's position among 79 countries on the ISI database. Three measures were constructed for all the countries from i=1 to N and for each of the fields from j =1 to K:

$PSH_{ij} = P_{ij} \Big/ \sum_{i=1}^{N} P_{ij}$., $CSH_{ij} = C_{ij} \Big/ \sum_{i=1}^{N} C_{ij}$. and $IMP_{ij} = \left(C_{ij} / P_{ij} \right) \Big/ \left(\sum_{i=1}^{N} C_{ij} / \sum_{i=1}^{N} P_{ij} \right)$.

IMP is highly unstable when there are very few papers and is clearly not defined at all if no papers are published. We omitted a country from the analysis of citation rates if it produced less than fifty papers in a field over the period from 1981 to 1994. We then recorded where Australia ranked in the world on the three measures. We record a tick if Australia is in the top eight in any field.

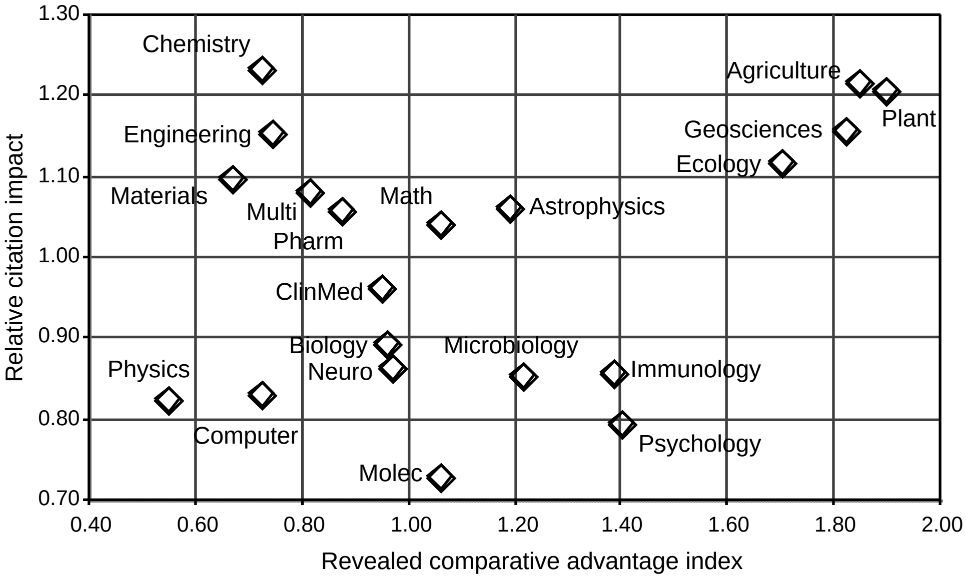
Source: ISI database.

Other fields have much lower indexes. The measures of RCA for chemistry (0.71), computer science (0.71), materials science (0.66), and physics (0.54) suggest some comparative disadvantage. We emphasise that these are **comparative** not absolute advantage measures. For example, in materials science, Australia has a 1.42 per cent share of the world's papers (11th in the world), 1.56 per cent of the world's citations (8th) and a relative citation impact of 1.1 (7th) – all of these suggesting that Australia has a better than average absolute standing in materials science relative to other countries (table 2.6). But even so, this field accounts for a relatively low share of Australia's total papers or citations compared to the world as a whole.

Interestingly, for Australia there is at best only a weak positive correlation between comparative advantage in a field and quality (figure 2.1). Certainly, the four natural science fields identified above all have well above average world citation rates, but disciplines like chemistry and engineering, where a distinctive comparative advantage is not revealed, are still well above average world citation rates. This is not an Australian oddity. We found that correlations were typically weak for other countries. And indeed for 14 of the 32 countries/regions in table 6.2 the correlation is negative.

This suggests that the pattern of specialisation by any country within scientific fields is not driven by the differences in quality between these fields.

Figure 2.1 Comparative advantage and quality



But what about revealed comparative advantage by field of science around the world? A few patterns emerge: countries with strong natural endowments, like Australia, South Africa, Chile, Norway and Indonesia tend to devote greater resources to scientific research and publication related to their economic endowments (figure 2.2). The smaller European economies (for example, Denmark, Sweden, Switzerland) have carved a niche in medical or medical related research. The more dynamic Asian economies have tended to specialise in published science related to industry (Singapore, South Korea, Taiwan and India). Finally, there are countries whose pattern of specialisation does not fit these categories. There are two distinct groups in this category. The first group comprises the most scientifically dominant in the world (for example the US, Japan, France and Germany). The second, are the least developed scientifically (Papua New Guinea, Thailand).

Two other important questions can be posed about patterns of advantage by field:

- to what extent do countries specialise in fields? (narrowness vs ***breadth***); and
- to what extent does relative citation impact vary between fields (potentially a measure of the ***evenness*** of quality)?

Figure 2.2 Patterns of comparative advantage in publications [a]

Medical (clinical medicine, immunology, molecular biology and genetics, pharmacology)	Denmark, Sweden, Finland, Switzerland, UK
Natural resource based (agriculture, ecology, geoscience, plant & animal)	**Australia**, Canada, Chile, Indonesia, Malaysia, Mexico, New Zealand, Norway, Philippines,South Africa
Industry based (engineering, computing, chemistry, materials science)	India, Singapore, South Korea, Taiwan
Other (mixed)	France, Germany, Japan, Italy, Netherlands, US, Hong Kong, PNG, Thailand

a We identified the top four fields for any country in terms of the ratio of citation share by discipline to citation share of the country as a whole. We then allocated a country to one of the categories above (either medical, natural, industry or other), if they had three or more of the associated fields in their top four.

Source: ISI database.

Measures of breadth and evenness based on the publications and citations data suggest that:

- Australia has **broad** scientific capabilities as measured by the shares of papers across 20 scientific fields[8] (figure 2.3). Not surprisingly Australia has less broad capabilities than the US, Canada and the major European economies, but greater broadness than Sweden, Norway and Japan. In the APEC region, Australia is third on this measure. Other countries, such as the Philippines and Indonesia are niche players – choosing to specialise in particular fields. But is broadness a 'good' thing? On the one hand, if a country has few resources to devote to science it seems sensible to make a few strategic choices that match some of the most pressing economic and social needs of the country. For developing economies it may well pay to select a few fields. On the other hand, broadness increases the technological and scientific options available to a country. Science and technology moves very rapidly and new areas of inquiry emerge which require background knowledge. For example biotechnology, superconductivity, nanotechnology are newer areas for research which are only open to countries which have the prerequisites in the right fields. Broadness is like portfolio diversification in share markets – it allows a country to spread its scientific and technological risks. This is important given the unpredictable nature of technological developments and the difficulties of foreseeing technological trajectories in an economy (box 2.1 and Bourke and Butler 1995a, pp. 2-3).

- Australia has the least variation in its (normalised) **relative citation impacts** [9] in the world, followed by the UK, Netherlands and France (figure 2.3). In the APEC

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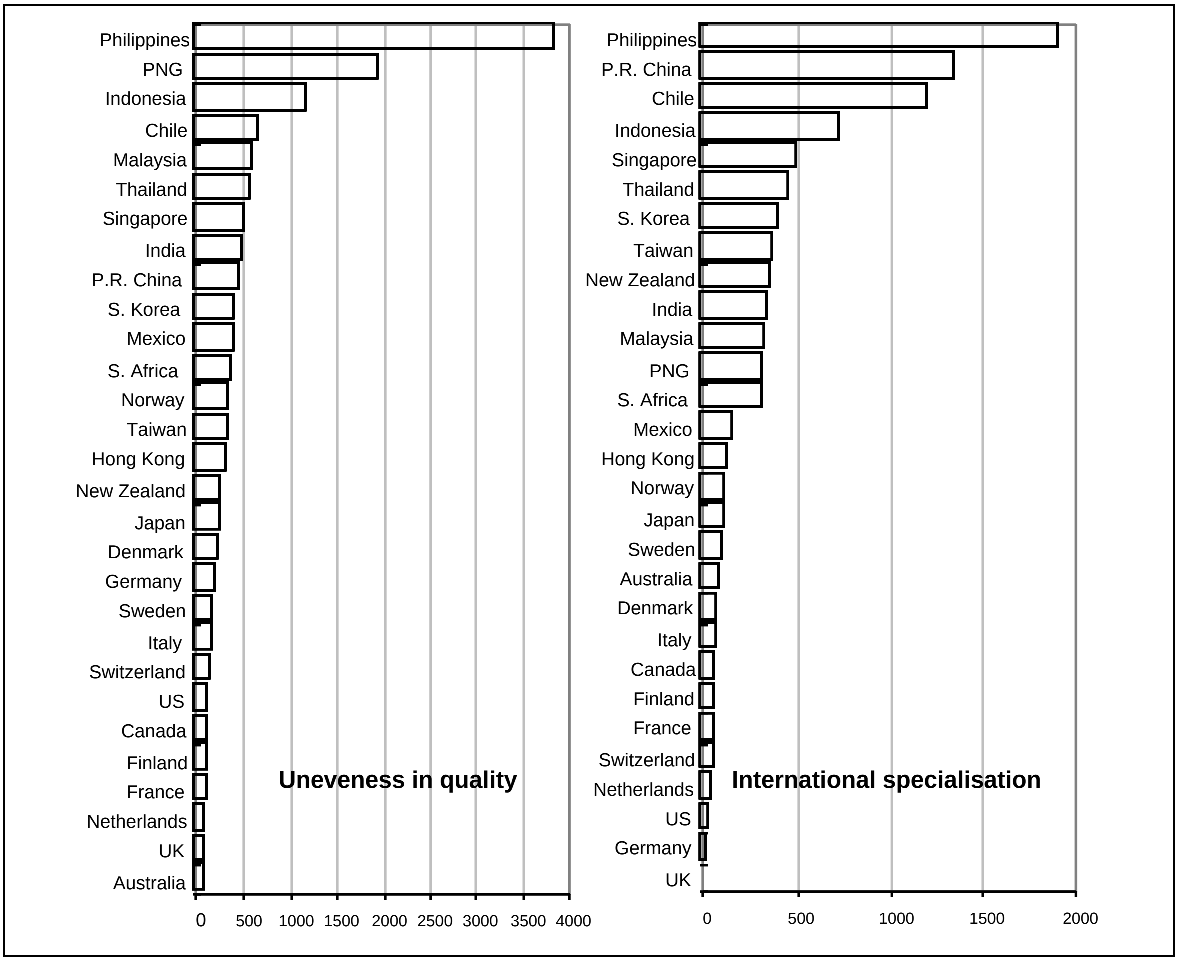
[8] To measure broadness we first measured the field shares of a country, normalised by the field shares of the world. That is we measured the disparity between a country's field share and the world's field shares $PDISP_{ij} = \left(P_{ij} / P_{World,j}\right) / \left(P_{i,all\ fields} / P_{World,all\ fields}\right)$ where P is the number of papers. We then calculated the variance of this measure across j for each country as our measure of narrowness. If a country's field shares exactly matched that of the world, then narrowness is zero (or broadness at its maximum). This may seem odd. After all you might suppose that if field shares within a country were exactly equal then such a country had the most broad scientific capability. But the problem with this is the concept of fields. Fields are simply pigeonholes for associating similar types of scientific inquiry. Some fields, like chemistry and physics, are very wide, covering many sub-fields, while others, such as astronomy, are narrower. By normalising a country's field shares by world field shares, we take account of the underlying breadth and importance of some fields. Figure 2.3 reports the variances of PDISP relative to Australia (with Australia=100.0). So for example, the variance of the normalised field shares is about twenty times greater in the Philippines than Australia.

[9] We measured the ***normalised*** relative citation impact in any field for any country as:
$RCIT_{ij} = \left(CR_{ij} / CR_{World,j}\right) / \left(CR_{i,all\ fields} / CR_{World,all\ fields}\right)$ where CR is the citation rate defined as: $CR_{ij} = (C_{ij} / P_{ij})$. The measure looks at relative citation rates by field, normalised by the overall citation impact of a country across *all* fields. We need to normalise so that we can meaningfully compare variances across different countries. We measured *evenness* of this measure by calculating the variance of RCIT across j for a given country. If a country has a high variance relative to other countries it means that the relative citation impact in some fields is much higher or lower than the average for that country. Figure 2.3

region, Australia, Canada and the US lead the pack, followed by far more variation in these rates for Japan, Hong Kong, Taiwan, South Korea and Singapore. Care must be taken in interpreting such measures of evenness. A country could have very little variation in its relative citation impacts because they were uniformly poor! However, we know that this is not true for Australia.

Figure 2.3 Evenness of quality and specialisation in science, 1981-1994 [a]



a Australia is indexed at 100 and measures of quality unevenness and specialisation are then measured relative to Australia. The higher the score on unevenness the more variable is quality across scientific fields, while the higher the score on international specialisation the more specialised is a country within certain scientific disciplines.

Source: Based on ISI data.

reports the variances of RCIT relative to Australia (with Australia=100.0). So for example, the variance of the normalised citation impacts is about forty times greater in the Philippines than Australia.

Box 2.1 The whimsical nature of technology

“Everything that can be invented has been invented” *Charles Duell, US Patent Office, 1899.*

“The computer has no commercial future” *IBM 1948.*

“X rays will prove to be a hoax” *Lord Kelvin.*

“That is how the atom is split, but what does it mean? To us who think in terms of practical use it means nothing” *Lord Richie Calder, 1932.*

“The possibilities of the aeroplane have been exhausted” *Thomas Edison, 1895.*

“Space travel is utter bilge” *Astronomer Royal, 1956* (one year before Sputnik).

Source: Milsted (1995) and White (1993).

2.3 Scientific proclivity

So far we have measured the quantity, visibility and quality of (codified) science around the world. But poorer and less developed countries must often concentrate on other things than a well developed science base. Thus a comparison between citation and publications shares between Australia and, say Thailand, is obviously not a fair one. We should take account of differences in population, income and other factors when comparing countries around the world (table 2.7).

Using this approach we still find Australia is contributing more to published science than its income or population would suggest. Australian scientists publish 1.6 times as many papers than would be normally expected given our income (table 2.7). This is considerably more than the US (1.3), Japan (0.5), Singapore (0.9), and South Korea (0.3) – but less than New Zealand (2.4), India (1.9), the UK (1.7), Israel (3.4) and a range of Eastern European countries.

The per capita contribution made by Australian scientists is well in excess of the world average – but this simply reflects the fact that most highly populated countries have low per capita incomes. We explore scientific proclivity more rigorously in box 2.2.

Table 2.7 Scientific performance adjusted for population and income, 1992

	Papers per GNP relative to world	*Citations per GNP relative to world*	*Papers per person relative to world*	*Citations per person relative to world*		*Papers per GNP relative to world*	*Citations per GNP relative to world*	*Papers per person relative to world*	*Citations per person relative to world*
Algeria	18.0	7.3	7.7	3.1	Malaysia	24.9	9.9	16.3	6.4
Argentina	34.9	19.4	49.3	27.4	Mexico	23.5	13.3	19.0	10.8
Australia	**161.2**	**141.5**	**649.9**	**570.5**	Morocco	50.9	16.3	12.3	3.9
Austria	81.3	78.0	425.0	407.6	Netherlands	160.0	188.9	765.8	904.1
Bangladesh	40.9	16.3	2.1	0.8	New Zealand	240.9	191.0	692.2	549.0
Belgium	108.8	115.8	530.6	564.9	Nigeria	92.7	17.9	6.9	1.3
Brazil	36.7	17.5	23.7	11.4	Norway	111.5	97.9	672.7	590.3
Bulgaria	479.4	166.4	149.0	51.7	Pakistan	30.8	9.4	3.0	0.9
Cameroon	48.5	16.6	9.3	3.2	PNG	80.1	27.4	17.8	6.1
Canada	184.4	183.3	892.2	887.2	P R. China	54.0	20.7	5.9	2.3
Chile	108.1	67.9	69.0	43.3	Peru	22.9	11.2	5.1	2.5
Colombia	16.6	12.2	5.2	3.8	Philippines	18.1	10.4	3.3	1.9
Costa Rica	95.0	55.6	43.5	25.5	Poland	271.7	138.4	121.3	61.8
Czech.	420.7	190.1	240.8	108.8	Portugal	52.9	37.2	92.2	64.8
Denmark	147.1	159.4	893.5	968.4	Romania	110.1	31.6	29.1	8.3
Egypt	193.2	47.7	28.9	7.1	Saudi Arabia	35.0	7.6	61.5	13.3
Ethiopia	95.5	33.2	2.5	0.9	Singapore	85.5	47.4	314.3	174.3
Finland	146.3	155.5	751.1	798.3	South Africa	103.2	53.2	64.4	33.2
France	96.5	92.4	501.9	480.5	South Korea	29.8	14.4	47.3	22.8
Germany	86.8	85.2	466.9	458.4	Spain	78.0	57.0	254.5	185.9
Ghana	54.7	16.2	5.7	1.7	Sri Lanka	47.0	17.9	5.9	2.3
Greece	113.2	63.8	192.8	108.7	Sweden	163.4	185.2	1031.3	1168.8
Hong Kong	47.7	30.6	171.2	109.9	Switzerland	138.6	199.7	1168.5	1683.8
Hungary	309.2	202.1	214.6	140.2	Taiwan	75.1	37.0	179.3	88.3
Iceland	100.5	128.0	560.9	714.0	Tanzania	200.6	92.6	5.2	2.4
India	186.2	55.2	13.5	4.0	Thailand	17.2	11.6	7.4	5.0
Indonesia	4.8	2.5	0.8	0.4	Trinidad.	64.0	14.3	58.9	13.2
Iran	6.4	1.8	3.3	0.9	Tunisia	65.2	20.8	26.2	8.4
Ireland	174.6	148.0	498.0	422.1	Turkey	43.2	13.7	20.0	6.4
Israel	345.0	319.6	1065.5	987.2	UK	174.7	199.0	726.1	827.3
Italy	60.6	54.1	289.6	258.5	Uruguay	38.9	20.8	30.4	16.2
Ivory Coast	33.9	26.7	5.3	4.2	US	129.1	172.8	701.2	938.3
Jamaica	119.9	49.4	37.5	15.5	USSR	187.4	45.3	109.9	26.6
Japan	52.5	43.8	345.8	288.5	Venezuela	33.0	16.9	22.4	11.5
Jordan	169.0	41.3	44.2	10.8	Zimbabwe	96.9	41.5	12.9	5.5
Kenya	214.6	131.7	15.5	9.5	**World**	**100.0**	**100.0**	**100.0**	**100.0**

Source: The bibliometric data are from ISI database. The real PPP adjusted GNP data are from the World Bank Stars data base except for Taiwan, which comes from the *Taiwan Statistical data book* (1993, Council of Economic Planning and development, Republic of China). The population data are from the *International Financial Statistics* (IMF, 1994, Vol. XLVII, Washington DC) and the World Bank Stars database.

Box 2.2 Scientific proclivity

Table 2.7 simply reports ratios of output measures to population and income. We wanted to explore this more carefully by testing the influence of population, income, language and nature of country on scientific proclivity. We regressed each of three measures (the natural logarithms of per capita citations, per capita papers and the percentage of papers cited) against the logarithms of per capita income, population, and a 'dummy' variable equal to one if a country used English as a major language. We wanted to test a number of hypotheses:

® do richer countries produce more or less papers than their per capita income would suggest?;

® do countries with English as their major language produce more or less than countries where English is not a major language? This is important as there may be a bias towards greater citations and publications of English language scientific articles, which then distorts our picture of how different countries are performing.

After trying some more general specifications we found:

$$\log(\text{Paper/Pop}) = \underset{(34.9)}{-18.8} + \underset{(20.0)}{1.14} \log(\text{GNP/Pop}) + \underset{(2.0)}{0.42}\ \text{English} \qquad R^2 = 0.80$$

$$\log(\text{Citation/Pop}) = \underset{(32.9)}{-20.0} + \underset{(20.0)}{1.38} \log(\text{GNP/Pop}) + \underset{(1.8)}{0.45}\ \text{English} \qquad R^2 = 0.83$$

$$\log(\text{Cited Papers/Papers}) = \underset{(13.5)}{-1.35} + \underset{(8.4)}{0.094} \log(\text{GNP/Pop}) \qquad R^2 = 0.48$$

All figures in parentheses are White's heteroscedasticity-corrected t statistics.

There *appears* to be a strong "English" effect. The model implies that papers and citations per person are over 50 per cent higher in English speaking countries. But the result is only barely statistically significant. As well, when we tried the model with two dummies, one for Anglo-Saxon English speaking countries and one for non-Anglo-Saxon English speaking countries we found that only the former had a significantly higher scientific proclivity. This suggests that something other than language, such as culture and social institutions, underlie the model results above. Note, however, that in part the result may reflect the choices made by the ISI in compiling their journal list.

The other interesting feature of the results is that not only do richer countries produce more papers and citations per capita than poorer ones (an unremarkable result) but that they produce more per dollar of GNP.

What do these results imply for Australia? The models suggests that our high income per capita and our English language, culture and social institutions would produce a high scientific proclivity. But the model is not perfect in predicting the outcome for Australia. We actually have a **higher** scientific proclivity than our income and cultural and linguistic background would suggest.

3 Internationally co-authored publications

3.1 Introduction

Data on internationally co-authored papers provide measures of the strength of cross-border scientific linkages (table 3.1). Just under 12 per cent of Australia's scientific papers were internationally co-authored in 1991. This is just above the world average of 11 per cent, but is below most Western European countries, where a high level of international co-publications is stimulated by strong S&T cross-country cooperation inside Europe.

Table 3.1 Share of national publications which are internationally co-authored

Country	*% share*	*Country*	*% share*
Australia	11.5	France	13.7
Japan	5.2	Ireland	22.8
United States	6.6	Italy	13.2
Belgium	19.5	Luxembourg	53.6
Denmark	17.3	Netherlands	13.4
Germany	14.2	Portugal	23.7
Greece	16.6	UK	11.0
Spain	12.5	EC with countries outside EC	8.3
		World	11.0

Source: European Commission (1994) Bourke and Butler (1994) for Australia. The datum for the world comes from the NSF (1993). All sources use ISI data and cover all papers from higher education, public science agencies and private institutions.

However, when intra-EC co-publications are excluded, the aggregate EC level of collaboration is only 8.3 per cent and Australia's relative standing rises. Australia also scores well above the USA and Japan. But this is not surprising. We expect that larger R&D performing countries will tend to develop more linkages within their own systems rather than outside. Even so, the data point forcefully to the idea of global rather than just national systems of innovation.

Furthermore, the globalisation of science is rapidly growing. Bourke and Butler (1994) report that the percentage of internationally co-authored scientific publications in Australia nearly doubled between 1982 and 1991, a finding that was replicated by

NBEET (1995) when higher education papers alone were examined. NBEET found that the proportion of internationally co-authored scientific papers produced by Australia's higher education sector grew from just under 12 per cent in 1981 to 21.6 per cent in 1992 (table 3.2).

Table 3.2 Internationally co-authored publications over time[a]

	UK	*Australia*	*World*
	(%)	(%)	(%)
1976	..	..	4.0
1977	..	..	4.3
1978	..	..	4.6
1979	..	..	4.9
1980	..	..	5.2
1981	18.0	11.7	5.5
1982	18.9	13	5.8
1983	18.9	13.9	6.2
1984	21.3	14.7	6.7
1985	21.2	14.1	7.1
1986	22.1	15.2	7.5
1987	23.5	15.2	8.2
1988	24.3	17.1	8.6
1989	25.4	16.8	9.1
1990	27.7	19.2	9.8
1991	29.1	20.2	11.0
1992	..	21.6	..
1981-1991 Trend %	4.7	4.8	6.6
1981-1991 change %	61.7	72.6	99.1

a It should be *emphasised* that the UK and Australian data are based on collaboration involving university scientists and do not include scientists employed elsewhere. The world data relate to all publications, not just those produced by universities. The data for the UK and Australia suggest much higher levels of collaboration than table 3.1 because of this definitional difference. The trend is the exponential growth rate estimated by regressing the logged values of the shares against a time trend.

.. not available.

Source: NBEET (1995, p.19 & 28) and NSF (1993, p.426).

Comparable data for the UK suggest a very similar growth path. As well, the European Commission (1994) notes that while the co-publication level of Japan is low, it has more than doubled in the last few years. Overall, the share of world publications which were co-authored grew by 100 per cent from 1981 to 1991 or at an annual growth rate of 6.6 per cent per annum (table 3.2). Thus the growth in Australian co-publications in recent years, while very high, mirrors a world trend.[1]

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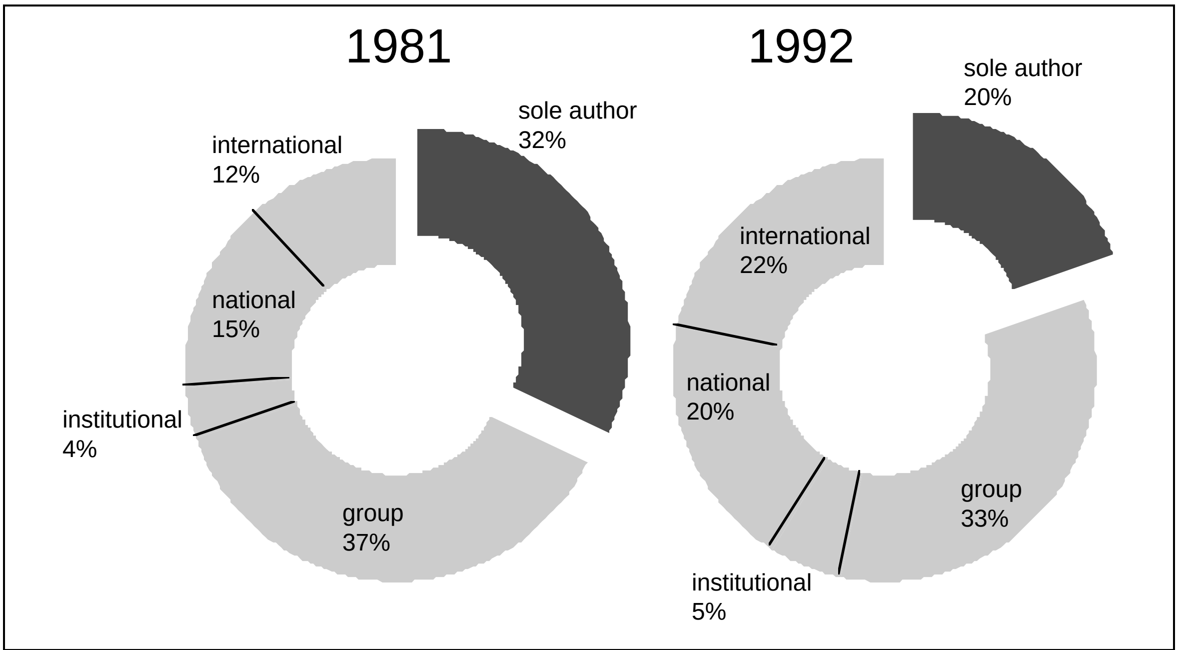
[1] However, an interesting exercise would be to collect data on the share of papers which are internationally co-authored for most scientifically active countries and then regress these shares against overall world publication shares of countries (and some other variables, such as geographical location, whether English is the common language etc). We could then see whether Australia, as a small and relatively isolated country, performs better or worse than expected. This exercise could also be performed using time series data to see whether Australia's international collaborative performance has been improving or deteriorating with time.

The trend represents more than just internationalisation – but also growth of linkages generally (figure 3.1). While nothing as extreme as the 'death' of the sole author is apparent, the really striking feature of the data on authorship is the strong decline in papers produced by a lone author. Teams – whether they be nationally or internationally based – appear to increasingly dominate the production of scientific knowledge.[2]

Figure 3.1 Type of authorship, Australian higher education scientific papers, 1981 and 1992[a]



a A sole author is one author only (no collaboration); a group is more than one author with the same departmental address, institutional is more than one author from different departments within the same institution, national is more than one author from different institutions in Australia and international involves authors from different countries.

Source: NBEET (1995, p.27 & 28).

3.2 Where does Australia collaborate?

The US and Europe – still the most powerful sources of basic scientific research – dominate Australia's academic scientific collaboration. Over the period from 1981 to 1992, nearly 80 per cent of Australia's academic collaborative papers were with the US, Canada, Western Europe and the UK. Just over ten per cent were with Asian

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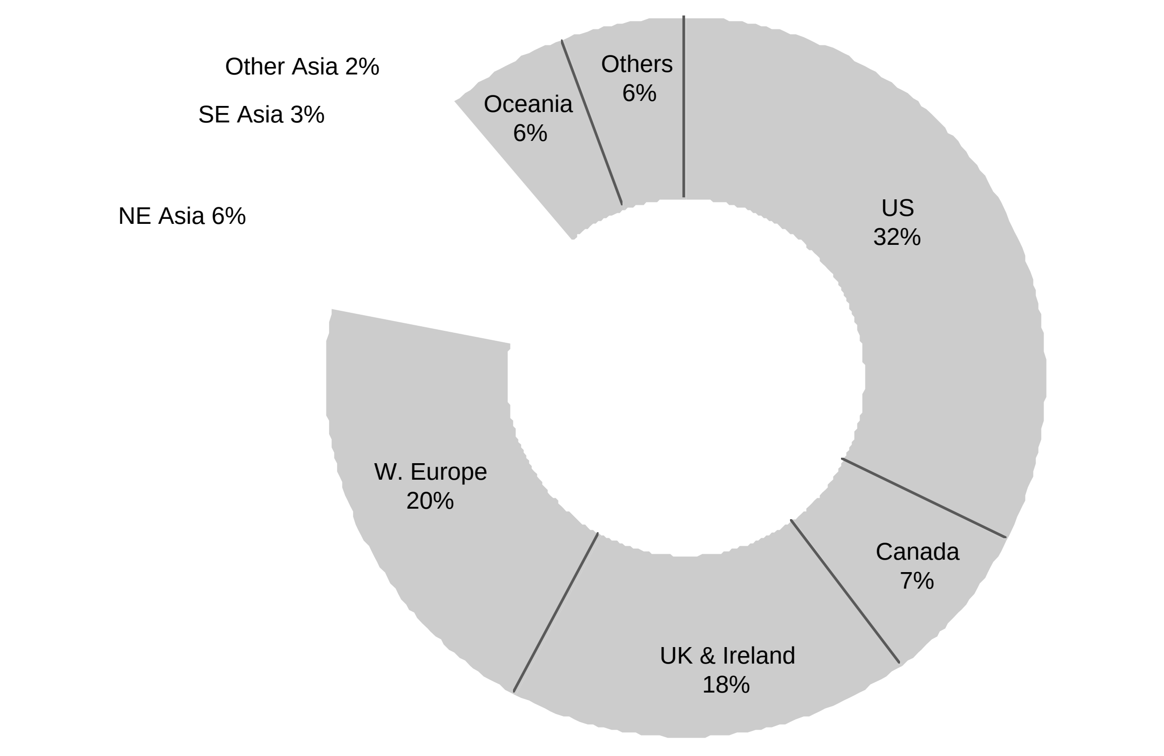
[2] Interestingly, team based research is on average more highly cited than sole authored research. For most fields, the greater the distance of the link, the more highly cited is the article. So, on average, sole authors are cited 86 per cent of the average citation rate, group authored articles 95 per cent, institutionally authored papers 98 per cent, nationally authored papers 106 per cent and internationally authored papers 115 per cent (NBEET, 1995, p.33).

countries (figure 3.2) and about six per cent were with Oceanic countries (mainly New Zealand).

Figure 3.2 Distribution of collaboration by region, 1981-92[a]



a In calculating the distributions above each non-Australian co-author in a publication is counted as one regardless of the number of co-authors and countries involved in any single publication. The data relate to the total period from 1981 to 1992.

Source: NBEET (1995, p.35).

However, this pattern is changing. Asian countries accounted for about 6.6 per cent of Australian internationally co-authored academic papers in 1981. By 1992, this had nearly doubled to 12.2 per cent (table 3.3). Particularly strong growth was apparent for papers authored with Japan and China. Interestingly, there has been negligible growth in the already weak levels of academic scientific collaboration with either Taiwan or South Korea – two of the most dynamic of the emerging scientifically developed economies of the region.

Collaboration with Western Europe has also grown significantly, with the share increasing by 53 per cent from 1981 to 1992 – but this has been mirrored by an almost equal waning of the UK.

Table 3.3 Australian international collaboration by region by time (percentage share of Australian co-publications)[a]

	US	*Canada*	*UK*	*W. Europe*	*NE Asia*	*SE Asia*	*Other Asia*	*Oceania*	*Others*

1981	36.4	8.4	21.2	15.0	2.7	2.4	1.5	7.0	5.3
1982	32.6	8.9	21.4	17.6	3.9	2.5	2.9	5.7	4.6
1983	34.8	7.6	21.0	17.9	3.8	3.1	1.8	5.9	4.0
1984	32.0	7.2	19.2	20.7	3.4	3.6	3.4	5.1	5.5
1985	31.7	7.9	19.8	20.0	4.2	2.6	2.2	6.8	4.7
1986	32.4	7.7	19.3	19.9	5.1	3.3	1.8	5.6	5.0
1987	33.5	7.1	18.9	19.5	5.6	2.7	1.9	6.1	4.7
1988	33.8	8.2	16.9	18.4	5.8	3.3	2.1	6.2	5.3
1989	33.0	6.8	16.2	22.9	6.2	3.3	1.8	5.6	4.2
1990	32.7	6.9	15.4	21.0	6.5	4.1	1.8	5.3	6.3
1991	31.5	5.8	16.8	21.7	7.3	3.1	2.0	4.2	7.5
1992	30.5	6.0	16.7	22.9	7.0	3.7	1.6	5.1	6.6
Trend growth[b]	-0.8	-3.0	-2.9	2.7	8.3	3.1	-2.2	-2.4	3.1

a In calculating the distributions above each non-Australian co-author in a publication is counted as one regardless of the number of co-authors and countries involved in any single publication. **b** The trend rate of growth was estimated by regressing the logged values of the shares against a time trend.

Source: NBEET (1995, p.35).

The pattern of collaboration by field varies across countries. For example, not surprisingly, Australia has strong collaborative links with Canada in earth sciences – because of a shared natural endowment (tables 3.4 and 3.5). The association with North America (US and Canada) is strong in mathematics and information sciences, while the association with Europe (UK and W. Europe) is strong in physics, chemistry and medical science. While there are distinct patterns of collaboration with the major scientific hubs of Europe and North America, these are much less sharply defined than those that emerge for Asia.[3]

The strongest links with Asia tend to be in applied science, information sciences and engineering – areas which reflect their comparative advantage. Outside of the industrialised economies in North East Asia there are also strong links in agricultural science.

Table 3.4 Percentage distribution of Australian higher education international co-publications 1981-92[a]

	Math	*Phys*	*Chem*	*Earth*	*Info*	*Appl*	*Eng*	*Biol*	*Agri*	*Med*	*Total*
	(%)	(%)	(%)	(%)	(%)	(%)	(%)	(%)	(%)	(%)	(%)
US	36.2	32.2	25.3	33.3	37.4	24.9	32.5	35.4	27.7	32.7	32.6
Canada	10.3	6.8	5.0	11.9	7.7	8.1	9.6	5.8	6.8	5.6	7.1
UK/Ireland	15.6	19.1	19.9	14.0	16.1	17.9	19.4	16.7	13.4	18.9	18.1
W Europe	18.4	24.6	24.1	17.4	16.8	13.3	12.2	21.9	15.4	22.2	20.3
NE Asia	4.4	5.6	5.0	6.7	7.4	10.2	8.3	5.5	5.1	5.8	5.5
SE Asia	3.1	1.0	4.1	2.2	5.2	9.5	6.7	3.2	10.7	2.7	3.3
Other Asia	2.5	1.2	2.7	2.5	1.0	4.6	3.8	1.2	4.0	1.3	2.0

[3] The variance of the scores of collaborative intensity is not very high across fields for these hubs, but grows significantly for other regions (table 3.5).

Oceania	3.0	3.3	8.7	7.2	3.2	7.0	2.8	5.7	8.6	6.1	5.6
Others	6.5	6.3	5.2	4.8	5.2	4.6	4.8	4.6	8.2	4.7	5.5
Total	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0

a Math is mathematics, Phys is physics, Chem is chemistry, Earth is earth sciences, Info is information sciences, Appl is applied sciences, Eng is engineering, Biol is biological sciences, Agri is agricultural sciences, Med is medical sciences and Total is all fields (including social sciences, humanities and multidisciplinary publications). Western Europe includes all Europe except Eastern Europe and UK/Ireland. NE. Asia includes China, Hong Kong, Japan, South Korea and Taiwan. SE. Asia includes Brunei, Burma, Indonesia, Laos, Malaysia, Philippines, Singapore, Thailand and Vietnam. Other Asia includes all other Asian countries. Oceania includes Polynesian and Melanesian countries plus New Zealand. In calculating the distributions above each non-Australian co-author in a publication is counted as one regardless of the number of co-authors and countries involved in any single publication.

Source: NBEET (1995, pp. 49-50).

Table 3.5 Scores of collaborative intensity by field by region, 1981-92[a]

	Math	*Phys*	*Chem*	*Earth*	*Info*	*Appl*	*Eng*	*Biol*	*Agri*	*Med*	*Variance*
US	1.11	0.99	0.78	1.02	1.15	0.76	1.00	1.09	0.85	1.00	0.018
Canada	1.45	0.96	0.70	1.68	1.08	1.14	1.35	0.82	0.96	0.79	0.099
UK/Ireland	0.86	1.06	1.10	0.77	0.89	0.99	1.07	0.92	0.74	1.04	0.016
W. Europe	0.91	1.21	1.19	0.86	0.83	0.66	0.60	1.08	0.76	1.09	0.047
NE. Asia	0.80	1.02	0.91	1.22	1.35	1.85	1.51	1.00	0.93	1.05	0.105
SE. Asia	0.94	0.30	1.24	0.67	1.58	2.88	2.03	0.97	3.24	0.82	0.941
Other Asia	1.25	0.60	1.35	1.25	0.50	2.30	1.90	0.60	2.00	0.65	0.429
Oceania	0.54	0.59	1.55	1.29	0.57	1.25	0.50	1.02	1.54	1.09	0.174
Others	1.18	1.15	0.95	0.87	0.95	0.84	0.87	0.84	1.49	0.85	0.045

a See previous table for mnemonics. The data above represent scores of the intensity of collaboration by discipline calculated simply by dividing each of the cell entries in the previous table by the corresponding row entry in the extreme right column. That is: $SCORE_{ij} = \{COLL_{ij} / \sum_{j=1}^{k} COLL_{ij}\} / (\sum_{i=1}^{N} COLL_{ij} / \sum_{j=1}^{k} \sum_{i=1}^{N} COLL_{ij})$ where $COLL_{ij}$ is the number of collaborative papers by country i with Australia in field j. This tells us whether a country has a higher or lower level of collaboration in a field than it does for science overall. The variance of the scores were calculated for each region. This tells us how variable the extent of collaboration is across fields for different regions.

Source: Data based on NBEET (1995, pp. 49-50).

So far we have only looked at Australia's regional pattern of collaboration without seeing how this fits into the web of scientific collaborative relationships that develop between countries. Using NBEET (1995) data we can explore more deeply this web of relationships between players in the region (table 3.6). Each column in table 3.6 shows the share of a country's collaborative articles with the countries shown in each of the rows. Thus 0.2 per cent of Australia's co-authored papers are with Taiwan and 0.8 per cent of Taiwan's co-authored papers are with Australia. The first row of the table shows the extent to which countries in the region are collaborating with Australia. For the major NE Asian economies of Japan, South Korea, Taiwan and China it appears that Australia is unimportant as a collaborative partner – with the US being dominant.

However, table 3.6 can be somewhat misleading in indicating the strength of collaborative relationships. In particular, Australia produces many fewer collaborative papers in this region than Japan, US, England or France – and so we would expect smaller shares. The question to ask is: given the number of Australia's collaborative papers how well do we perform relative to other countries? We adapted table 3.6 by normalising each of the shares to take account of this "size" problem (table 3.7). We found that Australia has stronger than expected collaborative arrangements with Japan, Singapore, Malaysia, Thailand and Indonesia and weaker ones with Taiwan, South Korea and Vietnam. Collaborative arrangements with China, Hong Kong and the Philippines are roughly at their expected levels.

Table 3.6 International collaboration (percentage share of each country's total collaborative articles with other countries), 1988-94 [a]

	Aust	*Taiw*	*Chin*	*Jap*	*SK*	*Sing*	*Mal*	*Phil*	*Viet*	*Thai*	*Indon*	*HK*
Australia	..	0.8	4.6	3.1	0.8	13.5	16.9	8.1	2.9	10.8	18.3	8.2
Taiwan	0.2	..	1.2	1.3	0.7	2.5	0.6	1.1	0.0	0.5	0.8	3.8
China	3.0	3.2	..	5.4	2.6	5.3	1.7	4.8	0.0	1.4	1.1	18.6
Japan	5.7	9.5	15.1	..	20.1	7.8	11.7	19.8	12.4	18.7	23.4	3.1
South Korea	0.2	0.8	1.0	2.9	..	0.5	0.8	2.5	0.4	0.6	0.7	0.4
Singapore	1.2	0.9	0.7	0.4	0.2	..	5.0	0.8	0.0	1.1	0.8	2.2
Malaysia	0.9	0.1	0.1	0.3	0.2	2.9	..	1.0	0.0	0.9	0.9	1.3
Philippines	0.4	0.2	0.4	0.5	0.5	0.5	1.0	..	3.3	1.6	1.7	0.3
Vietnam	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.8	..	1.0	0.1	0.2
Thailand	1.1	0.2	0.2	1.0	0.2	1.2	1.8	3.2	8.3	..	1.3	0.4
Indonesia	0.9	0.1	0.1	0.6	0.1	0.4	0.8	1.6	0.4	0.6	..	0.3
Hong Kong	1.1	2.1	3.9	0.2	0.2	3.4	3.4	0.7	2.5	0.6	1.0	..
US	46.7	73.1	47.2	62.0	64.2	30.6	23.5	41.2	20.7	37.0	29.9	30.1
Canada	10.4	3.8	9.8	7.1	3.6	8.4	5.0	4.0	3.3	6.0	3.9	8.9
England	22.8	3.5	9.1	8.5	2.9	21.0	23.2	6.0	10.8	14.9	8.6	21.0
France	5.5	1.7	6.6	6.5	3.7	2.0	4.4	4.4	34.9	4.4	7.7	1.1

a The country mnemonics in the top row follow the countries listed in the left hand column. To read the table, note the following examples. 0.8 per cent of Taiwan's total collaborative papers (where the total is based on only the countries listed) are with Australia while 73.1 per cent are with the US. In contrast 0.2 per cent of Australia's collaborative papers are with Taiwan. These data include collaborative publications from all sectors of the economy and are not isolated to the higher education sector.

.. not relevant

Source: NBEET (1995, p.49-50).

The low levels of collaboration with South Korea and Taiwan are not anomalous for Australia. Most countries in the region, with the exception of Japan, have low levels of academic scientific collaboration with these two countries.[4] Even so, the reasons underlying Australia's low level of collaboration with these emerging scientifically advanced countries should be pursued.

Table 3.7 Measures of the strength of international collaboration [a]

	Aust	*Taiw*	*Chin*	*Jap*	*SK*	*Sing*	*Mal*	*Phil*	*Viet*	*Thai*	*Indon*	*HK*
Australia	..	0.3	1.0	1.2	0.2	2.2	2.4	1.1	0.6	1.8	2.3	1.3
Taiwan	0.3	..	0.9	1.7	0.6	1.3	0.3	0.5	0.0	0.2	0.3	2.0

[4] As noted in table 3.7 we do not have data to be able to include the US in this analysis. However, there is little question that the US would be the major site of collaborative research for these two countries.

China	1.0	0.9	..	1.8	0.5	0.7	0.2	0.6	0.0	0.2	0.1	2.5
Japan	1.2	1.7	1.8	..	2.5	0.7	0.9	1.4	1.3	1.6	1.5	0.3
South Korea	0.2	0.6	0.5	2.5	..	0.2	0.3	0.8	0.2	0.2	0.2	0.1
Singapore	2.2	1.3	0.7	0.7	0.2	..	3.1	0.5	0.0	0.8	0.4	1.6
Malaysia	2.4	0.3	0.2	0.8	0.3	3.1	..	1.0	0.0	1.0	0.7	1.4
Philippines	1.1	0.5	0.6	1.4	0.8	0.5	1.0	..	4.6	1.8	1.4	0.3
Vietnam	0.6	0.0	0.0	1.3	0.2	0.0	0.0	4.6	..	6.7	0.5	1.4
Thailand	1.8	0.2	0.2	1.6	0.2	0.8	1.0	1.8	6.6	..	0.6	0.3
Indonesia	2.3	0.3	0.1	1.5	0.2	0.4	0.7	1.4	0.5	0.6	..	0.3
Hong Kong	1.3	2.0	2.5	0.3	0.1	1.6	1.4	0.3	1.4	0.3	0.3	..

a The country mnemonics in the top row follow the countries listed in the left hand column. The data are based on the following measure: $LINK_{iq} = (COLL_{iq} / COLL_i) / (COLL_q / TCOLL)$ where $COLL_{iq}$ is the number of collaborative papers of country i with country q, $COLL_i$ is the number of collaborative papers of country i with all other countries in the region and $TCOLL$ is the total number of collaborative papers in the region. The total will include double counting but this is necessary to ensure that the sum over q of $(COLL_q / TCOLL)$ adds to one. NBEET (1995) provide some further data on collaboration of the above countries with the US, Canada, England and France as in the previous table. However, we could not compute measures of the intensity of linkages using the NBEET data because data on total collaborative papers by these countries were not available. Note that the data above include collaborative publications from all sectors of the economy and are not isolated to the higher education sector.

.. not relevant.

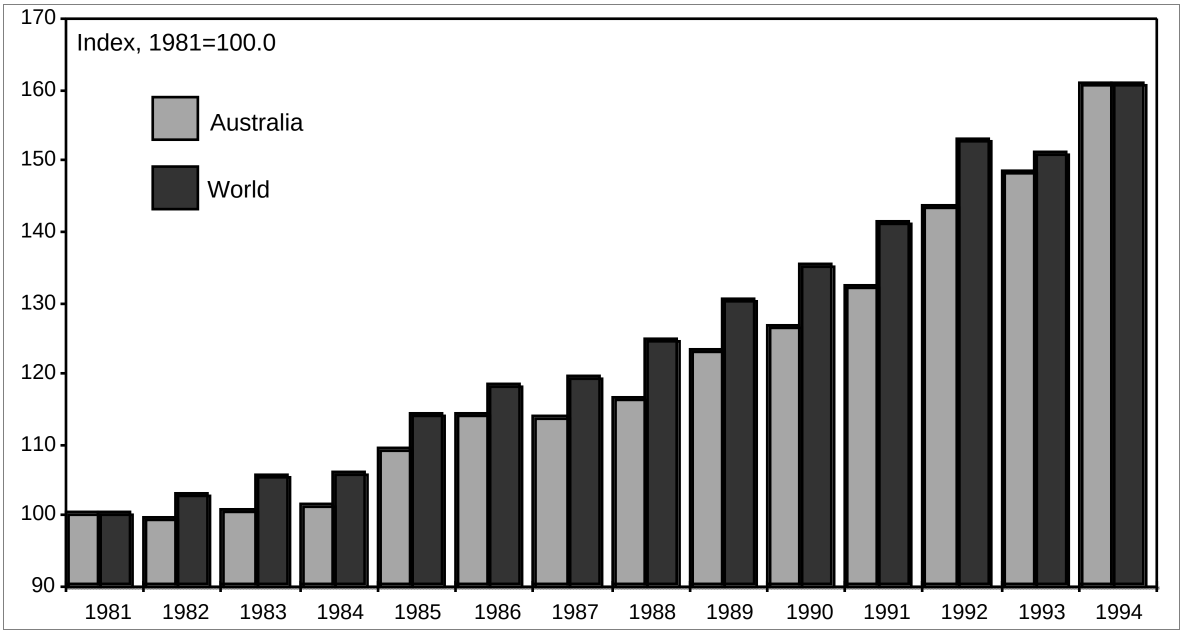
Source: NBEET (1995, p.49).

4 Australia's scientific publications and citations over time

4.1 Publications over time

Australia's production of scientific papers has grown strongly in *absolute* terms over the period from 1981 to 1994 – increasing at a trend rate of about 3.6 per cent per annum (figure 4.1 and table 4.1). Over this fourteen year period the overall number of annual scientific papers has increased by around 60 per cent. But much of this growth has occurred in the second half of the period. Growth from 1981 to 1987 was modest with only a 13.6 per cent increase in the number of papers. In contrast, in the period from 1988 to 1994 the number of scientific papers published increased by nearly 40 per cent.

Figure 4.1 Growth in Australian and world scientific papers, 1981 to 1994



Source: ISI database.

Table 4.1 Growth rates in scientific papers [a]

	1981 to 1987	*1987 to 1994*	*1981 to 1994*

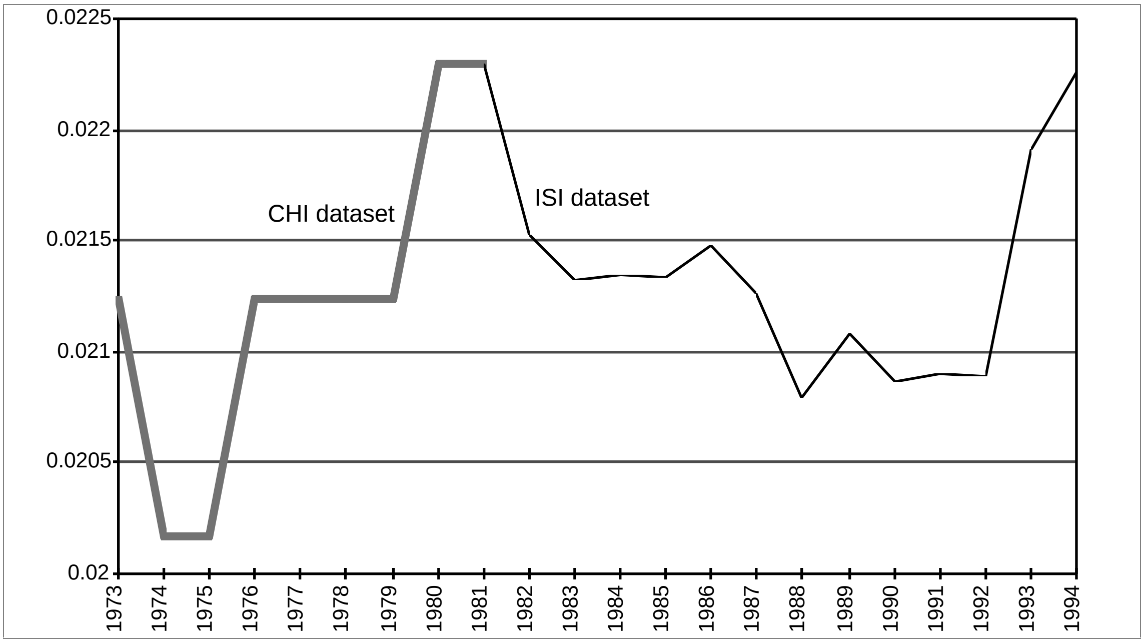
	Trend	Rank	Trend	Rank	Trend	Rank	Years to double
Australia	0.026	(50)	0.049	(47)	0.036	(21)	19.0
Canada	0.049	(31)	0.037	(59)	0.041	(17)	16.7
Chile	0.048	(32)	0.055	(40)	0.054	(13)	12.8
Denmark	0.021	(56)	0.054	(41)	0.036	(22)	19.5
Finland	0.045	(34)	0.065	(34)	0.049	(14)	14.1
France	0.032	(44)	0.052	(43)	0.044	(16)	15.9
Germany	0.024	(53)	0.041	(55)	0.033	(24)	21.1
Greece	0.081	(19)	0.089	(23)	0.087	(6)	7.9
Hong Kong	0.143	(9)	0.107	(14)	0.117	(5)	5.9
India	-0.002	(71)	0.018	(68)	0.011	(29)	61.4
Indonesia	0.061	(26)	0.096	(21)	0.079	(7)	8.8
Italy	0.057	(27)	0.078	(27)	0.068	(9)	10.1
Japan	0.054	(30)	0.060	(37)	0.058	(12)	11.9
Malaysia	0.020	(57)	0.091	(22)	0.062	(11)	11.2
Mexico	0.071	(24)	0.098	(19)	0.079	(8)	8.8
Netherlands	0.062	(25)	0.066	(33)	0.063	(10)	11.0
New Zealand	0.013	(62)	0.043	(50)	0.029	(26)	23.7
Norway	0.029	(46)	0.052	(44)	0.037	(20)	18.9
Papua New Guinea	0.039	(39)	-0.031	(74)	0.001	(30)	658.2
Peoples R. China	0.182	(6)	0.103	(16)	0.147	(4)	4.7
Philippines	-0.025	(76)	0.041	(52)	0.019	(28)	36.8
Singapore	0.207	(4)	0.153	(6)	0.161	(3)	4.3
South Africa	0.073	(22)	0.002	(71)	0.035	(23)	19.8
South Korea	0.214	(3)	0.216	(1)	0.216	(1)	3.2
Sweden	0.045	(35)	0.040	(56)	0.039	(19)	17.8
Switzerland	0.034	(42)	0.067	(32)	0.046	(15)	15.0
Taiwan	0.178	(8)	0.200	(2)	0.200	(2)	3.5
Thailand	0.016	(60)	0.077	(29)	0.040	(18)	17.5
UK	0.028	(47)	0.040	(58)	0.030	(25)	22.8
US	0.023	(54)	0.029	(63)	0.027	(27)	25.8
World	**0.032**		**0.043**		**0.037**		**18.6**

a The trend growth rates were calculated by regressing the logged values of the number of scientific papers against a time trend. The years to double the volume of papers was calculated as ln(2)/r where r is the exponential trend rate of growth.

Source: ISI database.

Australia's growth in papers has been roughly on par with world trends. Relative growth was lower during the 1980s and higher in the 1990s – so that at the end of the fourteen year period Australia's share of world papers was close to its value in 1981. We also examined a longer data set on publication shares (figure 4.2). These data suggest an erratic pattern, with the share fluctuating around 2.1 per cent. These data suggest that the present level is about 5 per cent above the historical average.

Figure 4.2 Australia's share of world scientific publications, 1973 to 1994[a]



a The Computer Horizons Incorporated (CHI) data is based on around 2300 journals covered by the Science Citation Index in 1973 (excluding psychology and social sciences). This series was spliced on to the ISI data set using backward recursion: $ISI_{t-1} = ISI_t \times (CHI_{t-1} / CHI_t)$ where ISI is the ISI value and CHI is the CHI value. The spliced data is indicative only because of differences in the coverage of the two databases and the lower precision in the CHI data.

Source: ISI database and CHI data from DITAC (1987, p.352).

But the *rate* of growth of codified scientific knowledge in Australia (and indeed most other advanced scientific countries) is paltry compared to some of the fast growing countries in the region. At the current rate of growth, it will take Australia nearly twenty years to double its count of papers. If present trends continue, this will take about four to five years for Singapore, China, South Korea and Taiwan.

4.2 Citations over time

Measuring papers is easy. We can simply look at how many papers were published in a given year. But measuring citations is far more difficult because citations for a given paper accumulate over time. In the ISI database there are two ways of dealing with elapsed time when recording citations: the *variable* and *fixed* window approaches.

The variable window method

For any given paper in any given year the current ISI database counts citations from that year until 1994. So a paper published in 1981 has 14 years of citations recorded, while a paper published in 1994 has only one year of citations recorded.

The fixed window method

Citations are recorded over a number of five year 'windows'. So as an illustration, for a paper written in 1981-85 the ISI will record only those citations occurring within that five year period. The database produces information on ten overlapping windows running from 1981-85, 1982-86 to 1990-94.

The advantage of the variable window method is that it uses the maximum data, but it suffers from two limitations:

- Papers of different ages have different chances of earning high citation rates. To overcome this we look at citation rates *relative* to other countries. Thus while it is true that an Australian paper in 1993 has only two years to be cited this is also true of a US or Canadian paper.

- The number of publications and citations in a given year can be quite small at the field level or for countries with smaller science systems. Fluctuations in the data tends to mask trends. Accordingly, for much of this chapter we use the fixed window data.

The data confirm the facts (but not necessarily the interpretation) first disclosed in *Science Watch* and amplified by Bourke and Butler (1994): Australian citation shares and relative citation rates are falling (table 4.2). It *appears* that there is a recovery in 1994 but we believe this is an illusion caused by the earlier citation of scientific articles written in English.[1]

A longer time series of data (constructed by splicing two datasets together) suggest that Australia's relative citation impact has risen and fallen in the past (figure 4.3). The mid-1970s represent, for example, a clear period of relative decline, close to that experienced since 1988. Overall, the series suggests a long run decline in the relative citation impact.

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1 Large revisions occur for final year data. For example, the measures of Australian citation shares and relative impacts for 1993 cited in the 1993 version of the ISI database were considerably lowered in the 1994 version. We expect the same will happen for the 1994 data in the 1995 database. The revisions in citation shares and relative citation impacts are much smaller after the second year of data.

While *relative* citation impacts have been falling – *absolute* citation rates have still risen in Australia over the last 14 years (figure 4.4). Interestingly, the very low growth in absolute citation rates from the late 1980s coincides with the rapid expansion of papers published by Australian scientists. This could be one of the keys to the reduced visibility of Australian science – and we look at it further later.

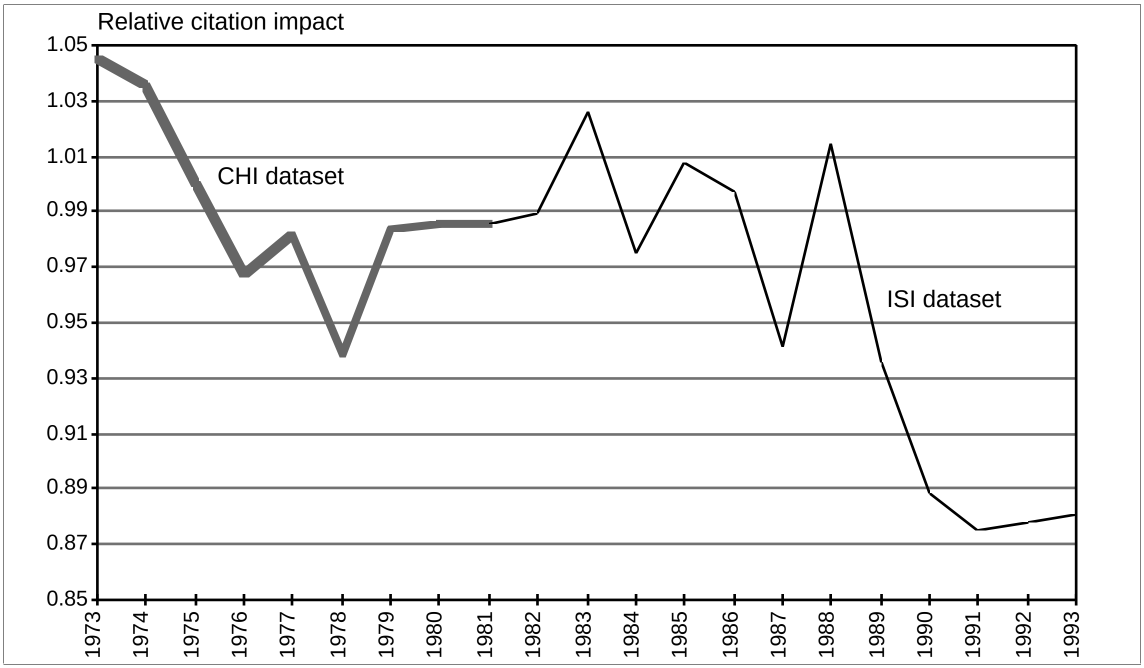
Table 4.2 Australia's scientific publication performance over time, 1981 to 1994[a]

Variable window data	*Share of world citations*	*Share of world papers*	*Share of world cited papers*	*Relative citation impact*	*Relative impact for cited papers*
1981	0.0220	0.0223	0.0243	0.986	0.905
1982	0.0213	0.0215	0.0236	0.990	0.903
1983	0.0219	0.0213	0.0233	1.025	0.938
1984	0.0208	0.0213	0.0233	0.975	0.893
1985	0.0215	0.0213	0.0231	1.008	0.931
1986	0.0214	0.0215	0.0234	0.997	0.916
1987	0.0200	0.0213	0.0230	0.942	0.871
1988	0.0211	0.0208	0.0227	1.014	0.928
1989	0.0197	0.0211	0.0228	0.936	0.864
1990	0.0185	0.0209	0.0226	0.888	0.821
1991	0.0183	0.0209	0.0222	0.875	0.824
1992	0.0183	0.0209	0.0222	0.878	0.827
1993	0.0193	0.0219	0.0231	0.881	0.836
1994	0.0211	0.0223	0.0235	0.949	0.900
Trend to 1993 (%)	**-1.53**	**-0.25**	**-0.53**	**-1.28**	**-1.00**
Fixed window data					
81-85	0.0206	0.0216	0.0238	0.957	0.868
82-86	0.0205	0.0214	0.0235	0.958	0.874
83-87	0.0205	0.0214	0.0233	0.962	0.881
84-88	0.0204	0.0212	0.0232	0.961	0.880
85-89	0.0206	0.0212	0.0232	0.972	0.886
86-90	0.0204	0.0211	0.0232	0.969	0.881
87-91	0.0199	0.0210	0.0228	0.949	0.872
88-92	0.0197	0.0209	0.0225	0.940	0.872
89-93	0.0189	0.0211	0.0225	0.896	0.844
90-94	0.0185	0.0214	0.0225	0.867	0.823
Trend to 90-94 (%)	**-1.10**	**-0.20**	**-0.63**	**-0.92**	**-0.49**

a The trend growth rates were calculated by regressing the logged values of the relevant variables against a time trend.

Source: ISI database.

Figure 4.3 Australia's relative citation impact, 1973 to 1994[a]



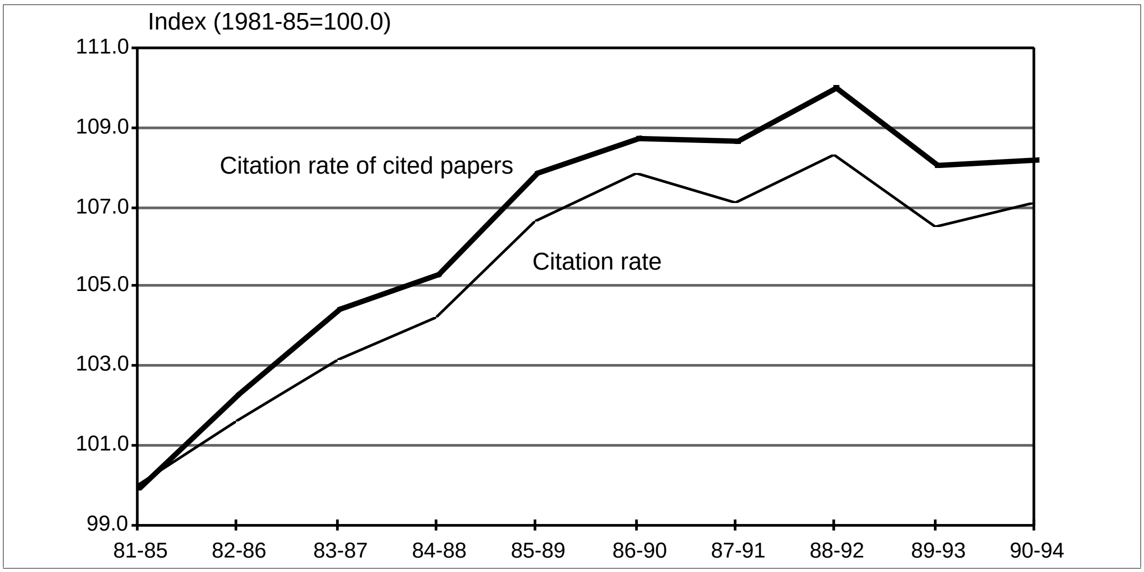
a We constructed the CHI measure of Australia's relative citation impact from 1973 to 1982 using more disaggregated data in DITAC(1987). We formed an all-fields score for Australia by calculating a weighted average of the citation impacts for 8 scientific disciplines (using the 1973 publications shares as the weights). We then spliced this series on to the ISI data set using backward recursion: $ISI_{t-1} = ISI_t \times (CHI_{t-1} / CHI_t)$ where ISI is the ISI value and CHI is the CHI value. The spliced data is indicative only because of differences in the journal coverage of the two databases, and errors from the weighting method used to form the CHI estimates.

Source: ISI database and CHI data from DITAC (1987, p.352).

Has the decline been uniform across fields or have some fields been responsible for much of the decline? We found that three fields had suffered particularly large reductions in *relative* citation impact (with trend declines of greater than 2 per cent per annum): immunology, chemistry and material science (figure 4.5). And two of these fields, immunology and chemistry, had experienced falling absolute citation rates as well.

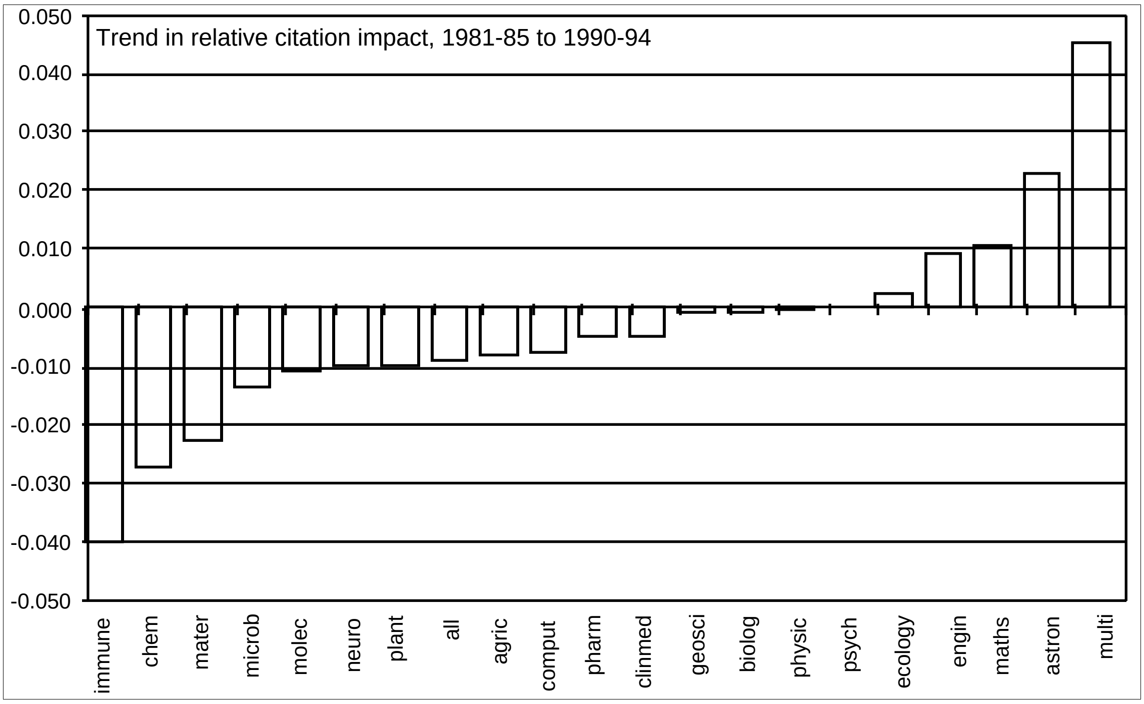
In the middle, there are thirteen fields subject to slight positive or negative trends in relative citation impacts (between minus and plus one per cent per annum). At the other end of the spectrum there are two fields (astrophysics and multidisciplinary science) with trend *increases* in relative citation impacts of over 2 per cent per annum. Clearly then, there have been considerable movements at the extremes, but with most fields sharing falls in line with the 1 per cent per annum general decline.

Figure 4.4 Citation rates in Australian science, 1981-85 to 1990-94



Source: ISI database.

Figure 4.5 Trend rates of growth in relative citation impacts by field, Australia a



a Trend rates of growth were calculated by regressing the natural log of the relative citation impact against a time trend. The mnemonics for the fields are detailed in appendix C.

Source: ISI database.

How have other countries fared and where are we in league ladder terms? It is useful when making these comparisons to break a country's relative citation performance into two components[2]:

- First, for a given country look at those papers which receive at least one citation, then gauge the citation rates for these papers relative to the world and finally see how this relative citation performance has changed over time.

- Second, look at those papers which are not cited at all. Then calculate the proportion of a country's papers which fall into this group. We can then compare this proportion with that of the world. Finally we can calculate how this relative proportion has shifted over time.

There was a trend decline of about half a percent per annum in the relative citation impact for Australian papers receiving at least one citation. This placed Australia in 54th position in the global league ladder – ahead of countries like Sweden, Denmark, South Korea and Taiwan – but well behind the US and UK.

In Australia's case there was a trend decline of just over 0.1 per cent per annum in the percentage of cited papers compared to the world where it grew at just over 0.3 per cent per annum. Thus the trend in the *relative* proportion of cited papers was just below -0.4 per cent per annum. This places Australia in 60th position among 79 countries, ahead of Japan, Malaysia, South Korea, Mexico and Norway and just behind countries like the UK and Denmark. Many countries with relatively underdeveloped systems have experienced the greatest growth rates in the percentage of cited papers (such as Senegambia, Vietnam and the Ivory Coast). Thus a low ranking for Australia should not be seen as a particularly adverse outcome.

Overall, Australia's relative citation rate fell by just under 1 per cent per annum from 1981-85 to 1990-94. Australia's ranking in terms of *growth* in relative citation rates was 56 out of 79 (table 4.3). Australia's position in the world league ladder of quality (as measured by relative citation impact) has fallen from 9th (1981-1985) to 16th (1990-1994) (table 4.4). But Australia's falling relative citation rate is by no means anomalous. Most of the advanced scientific countries were ranked in the bottom fifty percent of world performers. Countries like Denmark, Norway and Sweden have faced similar reductions in their relative citation rates. Nor is it the case that the newly industrialising countries have all experienced rapidly increasing citation rates: Taiwan

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[2] Namely the trend in relative citation impact $RCI = \bullet \ln (cit/pap)_a - \bullet \ln (cit/pap)_w = \bullet \ln (cit/cited)_a - \bullet \ln (cit/cited)_w + \bullet \ln (b_a/b_w)$ where **cit** is citations, **pap** is papers, **cited** is papers which are cited at least once, **a** and **w** denote Australia and the world and **b** is the share of papers which are cited.

and South Korea have also faced reductions in relative citation rates of the same order as Australia.

Table 4.3 Trend rates of growth in citation/paper performance, 1981-85 to 1990-94 [a]

	Share of world citations	*Share of world papers*	*Share of world cited papers*	*Relative citation impact*	*Rank*	*Relative impact for cited papers*	*Rank*
Australia	-0.011	-0.002	-0.006	-0.009	(56)	-0.005	(54)
Canada	0.005	0.003	0.003	0.001	(36)	0.002	(36)
Chile	0.013	0.020	0.024	-0.007	(52)	-0.011	(63)
Denmark	-0.012	-0.003	-0.006	-0.009	(58)	-0.006	(55)
Finland	0.012	0.007	0.008	0.004	(33)	0.004	(32)
France	0.013	0.007	0.010	0.006	(29)	0.003	(34)
Germany	0.005	-0.004	-0.002	0.009	(25)	0.007	(23)
Hong Kong	0.076	0.075	0.080	0.001	(38)	-0.004	(49)
India	-0.029	-0.024	-0.027	-0.006	(50)	-0.002	(42)
Indonesia	0.030	0.040	0.052	-0.011	(59)	-0.022	(72)
Italy	0.036	0.031	0.033	0.005	(30)	0.003	(33)
Japan	0.023	0.021	0.016	0.001	(37)	0.006	(24)
Malaysia	0.027	0.027	0.019	-0.001	(43)	0.007	(22)
Mexico	0.014	0.038	0.032	-0.024	(69)	-0.017	(69)
Netherlands	0.026	0.026	0.025	0.000	(39)	0.001	(40)
New Zealand	0.005	-0.009	-0.006	0.014	(19)	0.011	(12)
Norway	-0.012	-0.003	-0.008	-0.009	(55)	-0.004	(46)
PNG	0.022	-0.038	-0.023	0.060	(3)	0.044	(3)
PR. China	0.152	0.109	0.149	0.043	(7)	0.002	(35)
Philippines	0.015	-0.009	0.022	0.024	(15)	-0.007	(56)
Singapore	0.148	0.111	0.120	0.037	(9)	0.028	(4)
S. Africa	-0.007	-0.003	-0.003	-0.004	(46)	-0.004	(50)
S. Korea	0.154	0.178	0.169	-0.024	(68)	-0.014	(66)
Sweden	-0.010	-0.001	-0.001	-0.009	(54)	-0.009	(58)
Switzerland	0.004	0.006	0.006	-0.002	(45)	-0.003	(43)
Taiwan	0.161	0.171	0.174	-0.009	(57)	-0.013	(64)
Thailand	0.033	-0.004	0.033	0.037	(8)	0.000	(41)
UK	-0.011	-0.009	-0.013	-0.002	(44)	0.002	(38)
US	-0.008	-0.010	-0.010	0.001	(35)	0.002	(37)

a The trend growth rates were calculated by regressing the logged values of the relevant variables against a time trend.

Source: ISI database.

Table 4.4 The visibility and quality of science, 1981-85, 1985-1989 and 1990-94

	1981-85 relative citation rates		*1985-89 relative citation rates*		*1990-94 relative citation rates*	
	Rate	*Rank*	*Rate*	*Rank*	*Rate*	*Rank*
Australia	0.96	(9)	0.97	(9)	0.87	(16)
Canada	0.97	(8)	0.96	(10)	0.99	(10)
Chile	0.59	(28)	0.52	(38)	0.53	(36)
Denmark	1.24	(3)	1.12	(6)	1.13	(6)
Finland	0.90	(12)	0.91	(14)	0.95	(12)
France	0.88	(14)	0.90	(16)	0.93	(13)
Germany	0.88	(13)	0.90	(15)	0.96	(11)
Hong Kong	0.54	(34)	0.57	(28)	0.51	(38)
India	0.29	(66)	0.27	(66)	0.28	(66)
Indonesia	0.46	(41)	0.46	(41)	0.48	(43)
Italy	0.80	(18)	0.78	(20)	0.84	(18)
Japan	0.82	(16)	0.83	(17)	0.81	(19)
Malaysia	0.38	(51)	0.33	(58)	0.37	(55)
Mexico	0.60	(27)	0.55	(33)	0.48	(42)
Netherlands	1.15	(5)	1.14	(4)	1.15	(4)
New Zealand	0.70	(21)	0.82	(18)	0.80	(20)
Norway	0.93	(10)	0.91	(13)	0.86	(17)
Papua N Guinea	0.37	(54)	0.61	(26)	0.62	(27)
Peoples R China	0.24	(73)	0.28	(63)	0.35	(59)
Philippines	0.44	(44)	0.65	(25)	0.55	(33)
Singapore	0.31	(64)	0.39	(52)	0.45	(45)
South Africa	0.55	(31)	0.53	(36)	0.54	(35)
South Korea	0.49	(36)	0.41	(47)	0.40	(53)
Sweden	1.22	(4)	1.18	(3)	1.13	(7)
Switzerland	1.45	(1)	1.53	(1)	1.41	(1)
Taiwan	0.47	(39)	0.42	(45)	0.42	(48)
Thailand	0.43	(46)	0.56	(31)	0.63	(25)
UK	1.14	(6)	1.12	(5)	1.13	(5)
US	1.36	(2)	1.38	(2)	1.38	(2)

Source: ISI database.

It is instructive, as in Bourke and Butler (1994, p.49), to break the trend in the relative citation rate into two parts: the trend in the share of world publications and the trend in the share of world citations. We decompose the relative citation impact into these components because:

- it may be able to tell us something about the source of the change in the relative citation impact; and
- there may be a trade-off between the desire for visibility or quality (as measured by the relative citation impact) and the desire for a higher share of world publications. Thus a government, as the coordinator of the science system, might

be happy to see a small decline in relative citation rates if this accommodated an increase in the world publication share.

We graph the performance of all countries on these two measures in figure 4.6. If a country lies below (above) the diagonal line on the graph, then the trend in the relative citation impact of that country is positive (negative). We note that Australia lies (a) quite close to this diagonal line compared to many countries and (b) in a dense mass of other countries – so much so that we need to magnify this section to see any detail. This suggests immediately that Australia's position is scarcely exceptional. We are with the 'pack' – but running a little behind.

Second, as observed by Bourke and Butler, only a few countries share Australia's case of a relatively stable publication share and a declining citation share. How are we to interpret this? The answer depends very much on the sort of trade-off that governments wish between 'quality' and publications shares. For example, South Korea and Taiwan have experienced rapidly increasing citation and publications shares. But the growth of the latter has outstripped the former, so that their relative citation impacts have fallen. In this context, the overseers of these systems will probably not diagnose a crisis from falling relative citation rates. What does this trade off imply for diagnosing the health of the Australian system?

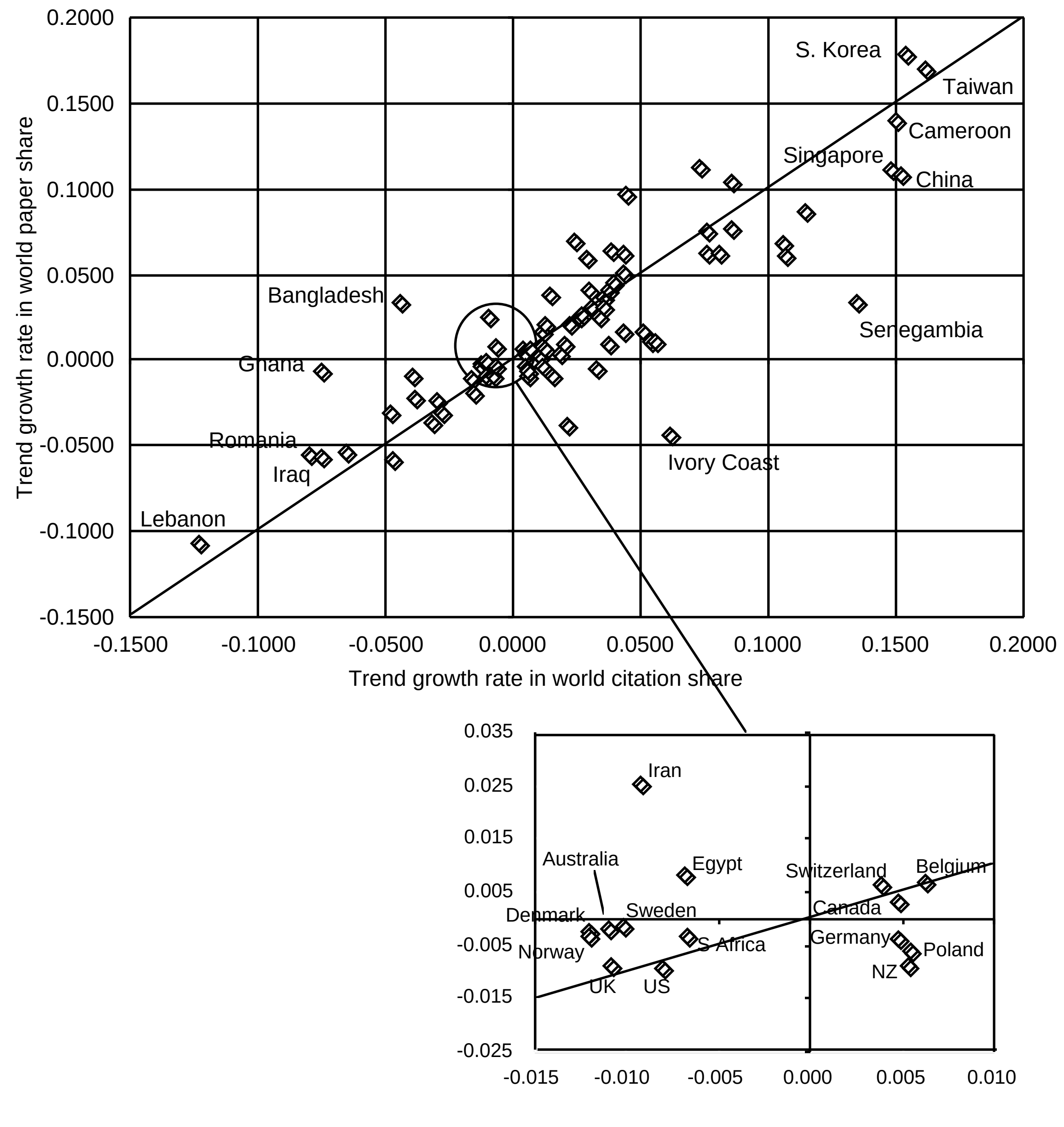
- There are countries like South Korea, Taiwan, Portugal and Turkey with equal or bigger falls in relative citation impact compared to Australia – but large increases in their penetration of world publications. Judged on the basis of relative citation impact alone, the performance over time of Australia's system may *seem* to be better than these countries, but the existence of the trade-off between publications and quality casts doubt on this.

- There are some countries, like the US and UK, with bigger falls in publication shares than Australia, but better growth in relative citation impacts. The trade-off implies that the trajectory of Australia's science system may be no worse than theirs.

- There are many other countries with only modest expansions of paper and citation shares and more severely falling relative citation rates than Australia (for example, Mexico, Pakistan and Uruguay). For many of these countries the tradeoff between publications and quality may not be enough to alter the ranking of the dynamic performance of their science systems compared to Australia. That is, it does not seem clear that the trajectory of Australia's science system is worse than another country with a more severely falling relative citation rate but only a modestly increasing publication share.

- Finally, there are countries with both falling citation impacts and falling publication shares. The existence of a trade-off implies that these countries are faring even worse than merely looking at the relative citation impact would imply.

Figure 4.6 Growth in paper and citation shares by country, 1981-85 to 1990-94[a]



Source: ISI database.

We now look at how Australia's performance by scientific field compares to other countries. We present detailed data on trend growth rates in world publication shares and in relative citation impacts for 20 fields and 29 countries in appendix C. Four interesting features emerge:

- Every country experiences a decline in the relative citation impact of at least 6 of the 20 ISI scientific fields. The ‘average’ country experiences a decline in 9 out of the 20 fields. Decline should therefore not be seen as exceptional: *it is normal*.

- The performance of Australia’s most adversely affected field (immunology with a 4 per cent reduction in its relative citation impact per annum) is roughly on par with the most adversely affected fields of other countries with developed scientific systems. But countries with less developed systems exhibit much more extreme reductions in their relative citation impacts for their most adversely affected fields (table 4.5). For example, the relative citation impact of immunology fell by a trend rate of 18.8 per cent in South Korea.

Table 4.5 Trends in relative citation impacts, high and low performing fields, 1981-85 to 1990-94

	Minimum growth rate	*Field with minium growth*	*Maximum growth rate*	*Field with maximum growth*	*Fields with negative growth*	*Range*
	(%)		(%)		No.	(%)
S Korea	-18.81	immunology	19.58	multidisciplinary	10	38.39
Mexico	-15.86	computer	6.61	clin. medicine	14	22.47
Taiwan	-11.50	ecology	8.89	astrophysics	7	20.39
Chile	-8.67	ecology	12.25	microbiology	9	20.92
India	-8.47	immunology	3.90	mathematics	11	12.37
Hong Kong	-8.26	multidisciplinary	8.49	microbiology	9	16.75
PR China	-6.89	computer	14.11	plant	6	21.00
Netherlands	-5.75	materials	2.87	clin. medicine	9	8.61
Norway	-5.64	mathematics	4.18	multidisciplinary	10	9.83
US	-4.99	multidisciplinary	1.29	agriculture	9	6.29
S Africa	-4.77	pharmacology	4.30	engineering	9	9.07
Denmark	-4.53	molecular biol	4.31	astrophysics	12	8.84
Australia	-4.05	immunology	4.48	multidisciplinary	15	8.53
Japan	-3.90	computer	5.45	multidisciplinary	8	9.35
New Zealand	-3.63	molecular biol	7.40	neuroscience	7	11.02
Switzerland	-3.38	molecular biol	5.38	multidisciplinary	8	8.76
Finland	-3.27	microbiology	5.85	multidisciplinary	8	9.12
Italy	-2.89	geoscience	3.93	computer	7	6.81
France	-2.75	materials	4.15	ecology	6	6.90
Sweden	-2.68	molecular biol	9.43	multidisciplinary	11	12.11
UK	-2.26	agriculture	4.01	pharmacology	12	6.28
Canada	-2.23	agriculture	4.22	multidisciplinary	7	6.45
Germany	-0.95	pharmacology	4.14	ecology	7	5.09

Source: appendix C.

- As well, the performance of Australia’s highest performing field (multidisciplinary with a 4.5 per cent increase in its relative citation impact per annum) is roughly on par with the highest performing fields of other countries with developed scientific systems. But just as before, countries with less developed systems exhibit much more extreme *increases* in their relative citation impacts for their highest performing fields (table 4.5). For example, the relative citation impact of multidisciplinary science increased by a trend rate of nearly 40 per cent in South Korea.

- Australia is unusual in that more fields have declined in impact than other countries. 15 of the 20 fields show a trend decline in relative citation impact from 1981-85 to 1990-94 (table 4.5). While many other countries show a more extreme decline in aggregate relative citation impacts, this can often be traced to just a few fields. Australia presents a case where the aggregate decline in relative impact has been relatively small – but is distributed over many fields.

- Related to the above two points, changes in relative citation impacts by field are much less variable in Australia compared to many other countries. Figure 4.7 depicts growth rates in relative citation impacts, sorted in ascending order for each country. The 'topography' formed by these growth rates reveals that the slope from the least performing field in Australia to the highest performing is relatively gentle and smooth. This is also true for most other scientifically advanced countries.[3] On the other hand, those with developing systems face a steeper and more jagged slope – their systems are far more turbulent than Australia's – an issue we return to later.

4.3 Possible reasons for the decline in citation rates

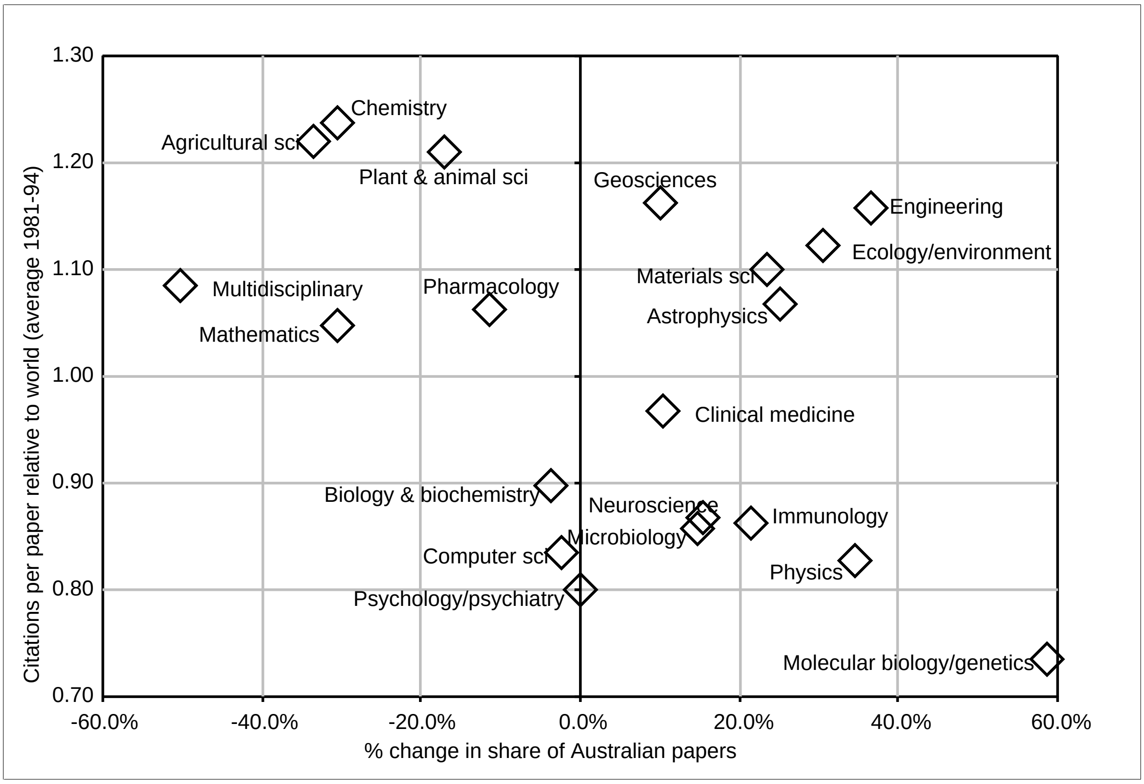
What are possible reasons for the decline? We consider a list of hypotheses for the pattern in the data**,** many of them originating from Bourke and Butler (1994) and from discussions we have had with observers of Australian science.

1. *Changes in the field structure of science, with a re-orientation to fields with lower citation rates?*

It is certainly true that over the last 13 years there has been a re-orientation from some fields where Australian science experienced high relative citation rates (figure 4.8).

[3] Another way of appraising this is to look at the range between the maximum and minimum growth rates in relative citation impacts for each country in table 4.5.

Figure 4.8 Structural change and quality in Australian science



Source: ISI database.

And some fields, like molecular biology, where Australia has a very low relative citation rate, have expanded rapidly. We explore structural change in more depth in the next section – but we find little evidence that shifts in field structure have had any more than a slight impact on the decline in Australia's relative citation rate.

2. Greying of science?

While we have incomplete data on the age profile of scientists, the evidence available does not point to a marked ageing of Australian scientists relative to other developed economies.

In any case, some of the countries where population age profiles are generally tilting towards the aged, such as Germany and Japan, have improved their relative citation impact. In contrast, in many of the Asian economies where there has been a rapid growth in the number of new (and therefore younger) scientists, relative citation rates appear to have fallen. In fact, it may be that *some* of the story of Australia's decline can be explained by an 'immaturity' effect: Australia's higher education system has expanded rapidly from the late 1980s. Perhaps new academics are cited less often than experienced ones? On the other hand, we doubt whether such an effect would yet show up in the data, except perhaps in the last few years.

In any case it should be noted that changes in the age structure of any large group typically evolve slowly, so that it seems implausible that the relatively abrupt change in Australia's relative citation performance in the 1980s can be principally ascribed to age distribution effects.

3. Inadequate total funding of infrastructure so that researchers do not have adequate resources to undertake high quality science?

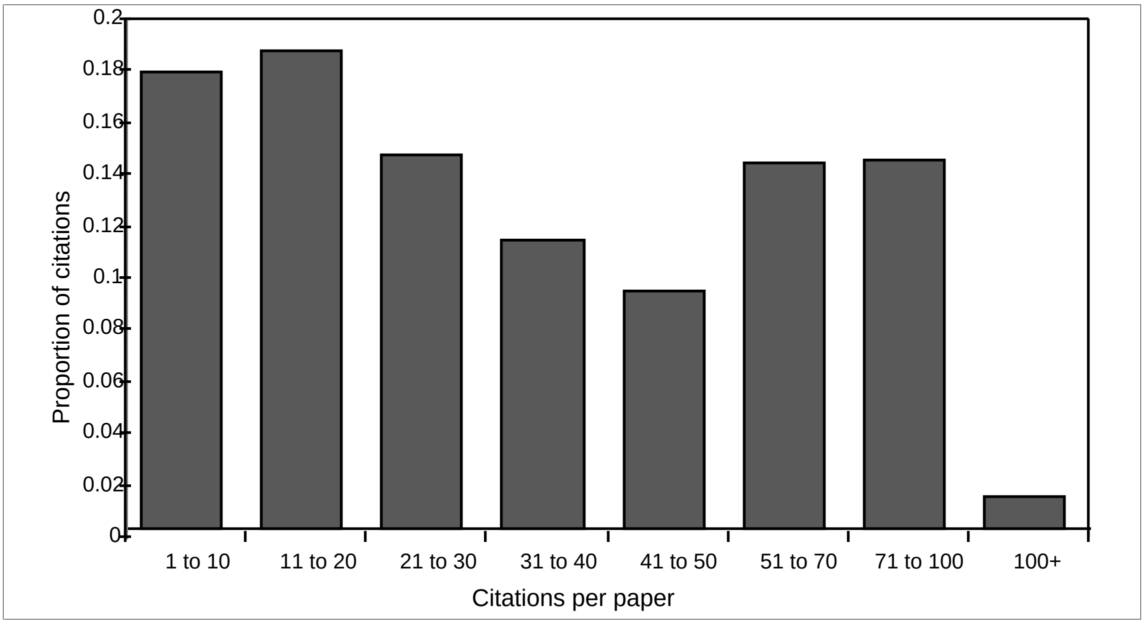
While we did not have detailed figures on infrastructure spending, we were able to gauge expenditure on fixed assets in public sector research (BIE 1996). The data suggests that there has been strong growth in expenditure per researcher from 1978-79 to 1990-91 followed by a fall in 1992-93. But what about other countries? Perhaps they have increased their expenditure at a faster rate? The answer is generally no. Nevertheless, more detailed research is required at the field level to gauge whether relative infrastructure inadequacies play a role in the decline. In particular, it has been widely observed that smaller countries find it difficult to afford some of the extremely capital-intensive areas of frontier science: so-called 'big' science (such as particle physics, superconductivity, and fusion research).

4. Changes in the distribution of resources?

There have been large shifts in the structure of the Australian higher education system in the last ten years – with the establishment of many new universities under the Unified National System – each with claims on resources. Not all science funding is determined by competition between researchers – so that it is possible that the expansion of the system may have diluted resourcing for the most able scientists and the best institutions. However, the major deficit in this argument is one of timing – the decline appears to have started *prior* to the change in the system. So while a shift in emphasis away from the pre-1987 universities may have a role in the continuation of the decline, it is probably not the trigger.

But there may be other reasons why resources have shifted away from the best scientists. One other way of testing whether resources have shifted this way is to examine whether there has been a change in the distribution of citations over time. We do not have the data to undertake this analysis. We do know, however, that 'high flying' articles (those with citations exceeding 50) account for about one third of all citations (figure 4.9). This means that changes in the resourcing for, or the number of, gifted researchers, can have a sizeable impact on aggregate citations.

Figure 4.9 Distribution of citations, Australia, 1981-90



Source: Data kindly provided by Paul Bourke and Linda Butler.

5. *An exodus of quality researchers?*

We were unable to appraise the influence of this factor. To do so carefully would require detailed data on the characteristics of outgoing and incoming scientists and the duration of their absence. The immigration data in BIE (1996) shows that Australia is a net gainer of scientific personnel – and this suggests we are still an attractive location for mobile international scientists. On the other hand, relative wage and salary rates seem to have shifted in favour of other countries – and this could put a pressure on the best to leave.

6. *A shift from basic to applied science?*

Public scientific institutions have been increasingly urged to undertake applied rather than basic research. Could it be that there has been a shift in the scientific orientation of agencies like CSIRO towards more practical – but less cited – research? The evidence suggests that citation rates have not suffered from any such shift. Data on citations rates provided by Bourke and Butler suggest that CSIRO increased its citation rate by around 20 per cent from 1981-85 to 1988-92, or roughly double the increase apparent for Australia as a whole.

7. Dislocations in the system?

There have been large institutional changes (in the public science agencies such as CSIRO and the changes brought about by the creation of the new universities) that could temporarily lower productivity and quality in science. As noted above, the data point to increases in citation rates in CSIRO relative to other parts of the Australian system.

Other than the dilution of resources, considered under point 4, changes in the university system may have had an impact in two other ways:

- the time taken to re-organise resources under the new system; and
- an increased flow of lesser quality (less cited) published articles from scientists in the new universities. In fact, the *counted* ISI publication output from the 'new' universities is slight (Bourke and Butler 1995b).[4] Accordingly, the new universities could only make a small difference to the relative citation rate via this route.

We consider that these changes are unlikely to explain the decline in relative citation rates experienced in the 1980s.

8. The visibility of Australian science has declined because Australian scientists are tapping networks less effectively?

Networks between scientists have an important role in scientific research. Such links include those fostered by (among others):

- Australian postgraduate students and post-doctoral researchers abroad;
- sabbatical leave;
- incoming high quality foreign scientists and postgraduate students;
- shared use of facilities;
- participation in conferences and seminars;
- informal discussion groups between scientists; and

[4] Indeed, the number of ISI listed papers per researcher is significantly lower in the new universities at around 0.6 per person compared to the pre-1987 universities at around 5.2 per person (Lowe, 1995).

- mobility between universities and other institutions.

Any factors which weaken the establishment and maintenance of such networks can (a) weaken Australian scientist's access to frontier ideas and techniques, thus affecting quality and citation rates and/or (b) lower the visibility of Australian science thus lowering citation rates. On the other hand, the rate of change of internationally co-authored papers with an Australian author (one measure of the degree of access to such networks) seems to be high and roughly in line with other countries. As well, we find it implausible that changes in networks alone could explain the relatively abrupt nature of the change in the later 1980s, although they may be a contributing factor.

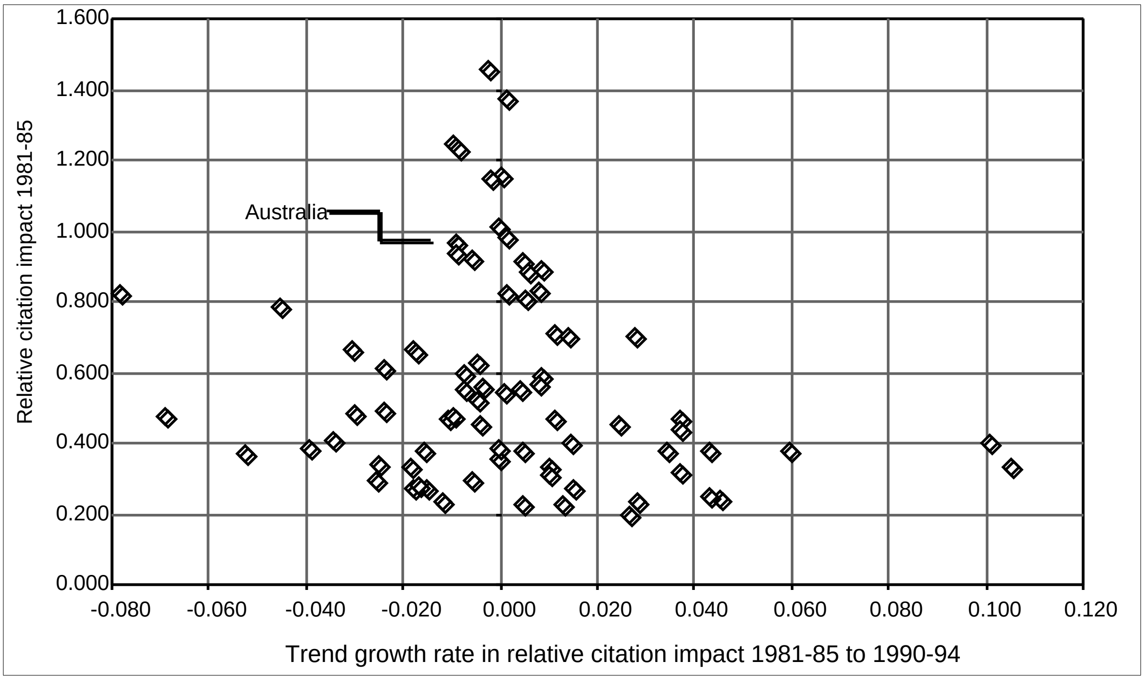
9. The quality of Australian papers hasn't fallen, but the improving quality of maturing science systems around the world has displaced some Australian papers?

Many developing economies have experienced rapidly increasing citation rates. It is possible that this could lower relative citation rates for Australian papers due to displacement effects.

Is the scope for improvement greater for science under-performers than high performers (like Australia)? How does this affect our interpretation of the citation rate data? We looked at this issue by seeing whether there was any relationship between improvement in science quality (as measured by relative citation rates) and the initial level of performance. We found that those countries with low relative citation rates in the period from 1981-85 tended to achieve greater improvements in their relative citation performance than countries which had high initial relative citation rates (figure 4.10). But the relationship was very weak. There were many countries which defied the trend – with some of the good getting better and some of the bad getting worse. Nevertheless, the model predicted that Australia would face a trend decline in relative citation impacts of around 0.7 per cent per annum (compared to the actually realised reduction of just over 0.9 per cent).

While we think convergence towards 'better' science might explain some of the shift in our relative citation rates, a puzzle remains. Why have so many of the other advanced scientific countries not experienced similar displacement? We conjectured whether one possible answer might be that Australia's field strengths are more closely aligned with the countries which are experiencing the most rapidly increasing citation rates. In this case Australian papers would be disproportionately affected by any displacement. But in fact, the decline in citations span most fields (and indeed is less in the resource based fields where we have the greatest field strengths).

Figure 4.10 Is there convergence in scientific performance? [a]



a We estimated a simple model of convergence by regressing the trend change in the relative citation impact (from 1981-85 to 1990-94) against a constant and the initial value of the relative citation impact (in 1981-85):

$$\Delta \, ln \, \hat{RELC} = -0.00789 - 0.01404 \, ln \, RELC_{1981-85}$$

(2.2) (2.8)

The t statistics are corrected for heteroscedasticity. Note that the model has poor fit, explaining only about 5 per cent of the variation in relative citation impacts.

Source: ISI database.

10. Foreign libraries have poorer access to ISI journals which disproportionately feature Australian scientists?.

Journal costs have risen rapidly in recent years. For example, average medical periodical prices in the UK increased from £124 in 1989 to £226 in 1994 (an increase of 82 per cent) while those in science and technology increased from £214 in 1989 to £402 in 1994 (an increase of 88 per cent) (LISU 1995). This has rationalised library purchases at a time of increasing demand by students and researchers. In the US, Perrault (1995) found that academic library collections are beginning to look more and more alike – with an increased concentration on core materials. To the extent that Australian papers are disproportionately represented in the ‘peripheral’ journals making up the ISI journal list, we would expect declining citation rates. This is a case where the decline would have to be seen as declining visibility rather than quality.

*11. Maybe relative citation impacts only **appear** to have fallen?*

Data problems could cloud the real long term citation impact of Australian papers. What data problems could matter?

- Is the ISI journal coverage increasingly biased against Australia? As noted by Bourke and Butler (1994), the use of dynamic rather than fixed journal sets are unlikely to alter citation results significantly, but this warrants further exploration.

- Is the treatment of collaboratively written papers biasing the results? Collaborative papers receive more citations on average than single authored papers. Perhaps Australians are collaborating less? In fact, the proportion of Australian papers which involve international collaboration doubled from 1982 to 1991 (Bourke and Butler 1994).

- Australians scientists who are temporarily abroad and submit papers while at a foreign university may have these recorded as papers coming from the foreign country, not Australia. Of course, the converse is true for foreign scientists in Australia. Nevertheless, any change in the number or duration of stays by visiting scientists, either Australians abroad, or foreigners here, could affect relative citation rates.[5]

- As noted previously, citations take time to accumulate. The way the ISI database deals with this accumulation can lead to false pictures of declining citation shares (appendix D). We do not have the data to confirm whether this is true or not.

12 The expansion in the number of researchers has diminished the average quality of the pool of scientists?

This is nothing more than a re-statement of the old principle of diminishing returns. We find some evidence in favour of this hypothesis – but we still find some strong counter-examples. For example, in Singapore the numbers of scientists have expanded rapidly, papers per scientist have grown and relative citation impacts increased.

[5] This also assumes that the citation rates of the mobile scientists are different from those that stay at home.

4.4 A model of the decline in citation rates

We attempted to understand relative citation impacts by estimating a statistical model using time series and cross sectional data for a range of OECD countries (box 4.1).[6]

Box 4.1 Modelling the falling relative citation rate

We supposed that relative citation impacts might depend on:

- resourcing for research and development. We measured this as per capita spending on R&D by government, higher education and other (mainly business), all in constant price $US.
- the quality of the scientists and engineers. We measured this as the numbers of papers per research scientist/engineer.

We estimated the following model to describe the relative citation impact (RELC) [7]:

RELC = 0.43 + 3.8 HRD/POP + 1.42 GRD/POP + 0.91 ORD/POP + 0.53 PAP/RSE (7.0) (4.3) (2.1) (3.6) (4.7)

$R^2 = 0.60$, N=145

where the figures in parentheses are White's t statistics.

HRD is higher education R&D expenses ($US million 1985 prices);

GRD is government sector R&D expenses ($US million 1985 prices);

ORD is other (primarily business) R&D expenditure ($US million 1985 prices);

PAP is papers;

RSE is research scientists and engineers; and

POP is thousands of people.[8]

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6 We used data from the 1994 ISI database on relative citation impacts for the years 1981 to 1993, and then collected data for OECD countries on R&D expenditures and RSE for any of these years. For some countries, including Australia, data for all years were not available.

7 We also included time dummies in the model, which we have omitted from the presentation of results since they are only there to correct for a possible bias. What bias? We are trying to explain *relative* citation impacts. It may therefore seem necessary to express all the independent variables in relative terms too. For example, should we use papers per RSE, or papers per RSE *relative* to the world average of papers per RSE? In fact, so long as a dummy variable is included for each time period, we can use the absolute measures and let the dummies act as the world averages. We do not include the dummies as they are really 'nuisance' variables intended to compensate for the form of the independent variables we are interested in.

8 The data relate to the period from 1981 to 1992. Not all data are available for all countries for all years. The bibliometric data are from the ISI database. The population and R&D expenditure data are from the OECD while the RSE data are from the OECD and chapter 8.

The results suggests that the impact of increasing higher education R&D spending per capita has a greater impact on relative citation rates than other government R&D expenditure, which in turn has a greater impact than business R&D. The model suggests that if a country's people each contributed another ten dollars (in 1985 prices $US) to higher education R&D then the country's relative citation impact would rise by about 3.8 percentage points. Of course, this is an average result only – any given country might find the impact greater or lesser than this.

The model may partly explain why countries with a strong industrial orientation in their R&D (such as Japan) tend to have less relative citation impact than those who allocate these R&D resources to higher education. We are not asserting that either configuration is better than the other – merely that choices about where to devote R&D has implications for a country's relative performance in codified scientific knowledge.

Perhaps more interestingly the model suggests that as the number of papers per researcher rises, the greater is the relative citation impact. In Australia, there has been a fall in the papers published per researcher – which in part may explain why our relative citation impact has fallen (but of course invites the question as to why the papers per researcher might have fallen).

We can use the model to understand how movements in resources and the 'productivity' of researchers may have influenced Australia's relative citation score from 1981 to 1990 (table 4.6).

The model *suggests*[9] that:

- the increase in higher education R&D expenditure led to a modest increase in Australia's score (by about 0.7 percentage points);
- this was more than offset by the influence of falling government R&D expenditures per capita;
- notwithstanding the small multiplier associated with business R&D expenditure, the massive increase in business R&D led to an increase in Australia's relative citation impact by around three percentage points; but
- the conspicuous fall in the number of papers published per researcher led to a nearly 7 percentage point drop in Australia's score – this appears to be the dominant factor underlying the fall in Australia's relative citation impact. It seems

9 We emphasise the word 'suggests', since these are the results of a statistical model based on a limited number of years of data and a very heterogeneous group of countries. That, combined with fears over the magnitude of errors in the data, makes us cautious about being more definitive.

plausible than the expansion in the number of scientists and engineers in Australia over the last decade may have lowered average quality. As a country expands its science system it tends to draw on less talented researchers and paper productivity and relative citation rates fall. This does not mean that the solution is to cut the number of researchers to raise quality. After all, if this line of logic were taken to an extreme this would suggest it is optimal to have just one brilliant scientist producing path breaking papers. It may well be optimal to increase the number of researchers even if this has the effect of depressing relative citation rates so long as the additional researchers produce outputs which are valuable and do not take away scarce resources from their better peers.

Overall the model 'explains' most of the fall in Australia's relative citation rate from 1981 to 1990.

Table 4.6 What does the model imply about the change in Australia's relative citation impact between 1981 and 1990? [a]

	HRD/POP	*GRD/POP*	*ORD/POP*	*PAP/RSE*	*Total*
1981	0.0422	0.0665	0.0388	0.4339	..
1990	0.0440	0.0549	0.0710	0.3016	..
Explained change	0.0070	-0.0165	0.0295	-0.0696	-0.0497

a HRD/POP is higher education R&D expenses per person ($US million 1985 prices); GRD/POP is government sector R&D expenses per person ($US million 1985 prices); ORD/POP is other (primarily business) R&D expenditure per person ($US million 1985 prices); and PAP/RSE is papers per research scientists and engineers

4.5 Structural change in science fields over time

Structural change is important because (a) it can disrupt a system if it is too rapid, with consequences for output and quality, (b) it can make it difficult to compare performance over time and (c) it tells you something about the direction of a science system.

Structural change (as measured by changes in the shares of papers by field) has been relatively modest compared to most other countries. Australia is ranked 65 in 79 countries in terms of the degree of structural change (table 4.7).

However, structural change has been appreciably greater than that experienced by many other advanced scientific countries – with the US, UK, Canada, Denmark, Finland, France, and Switzerland all facing less change. Like many other countries, there seems to have been a significant shift to clinical medicine in Australia.

But what of shifting revealed comparative advantages? Have the historical patterns of advantage been replicated in the 1990s? We find for Australia that the old advantages have been strengthened (figure 4.11).

Table 4.7 Structural change in science, 1981-85 to 1990-94 [a]

	Structural change score	*World rank*	*field with highest relative Increase [b]*	*field with greatest relative decrease [c]*
Australia	7.7	65	clinmed	chem
Canada	5.0	78	agric	physic
Chile	10.9	47	chem	biolog
Denmark	6.8	70	plant	clinmed
Finland	7.5	67	plant	clinmed
France	7.2	68	biolog	clinmed
Germany	6.7	71	physic	clinmed
Hong Kong	14.6	35	clinmed	biolog
India	9.7	54	clinmed	multi
Indonesia	15.8	32	plant	clinmed
Italy	6.9	69	clinmed	chem
Japan	9.7	53	clinmed	chem
Malaysia	13.2	39	chem	plant
Mexico	15.3	33	plant	clinmed
Netherlands	6.5	72	clinmed	physic
New Zealand	8.5	59	clinmed	agric
Norway	8.3	60	plant	clinmed
Papua New Guinea	13.9	37	agric	plant
Peoples R. China	25.7	5	physic	multi
Philippines	21.6	10	plant	clinmed
Singapore	19.4	17	engin	clinmed
South Africa	11.5	45	plant	clinmed
South Korea	8.1	63	engin	chem
Sweden	8.2	61	plant	clinmed
Switzerland	6.0	75	biolog	clinmed
Taiwan	20.6	15	engin	plant
Thailand	24.1	6	plant	clinmed
UK	6.0	76	clinmed	engin
US	4.3	79	chem	psych

a The Lawrence measure of structural change (SC) was employed. This is bounded between 0 (minimum structural change) and 100 (maximum structural change). thus $SC = 50 \times \Sigma_{j=1}^{K} \left| \alpha_{jt} - \alpha_{jt-1} \right|$ where α is the share of papers in each field. b The change in field shares (relative to the world) was calculated for each country and field:

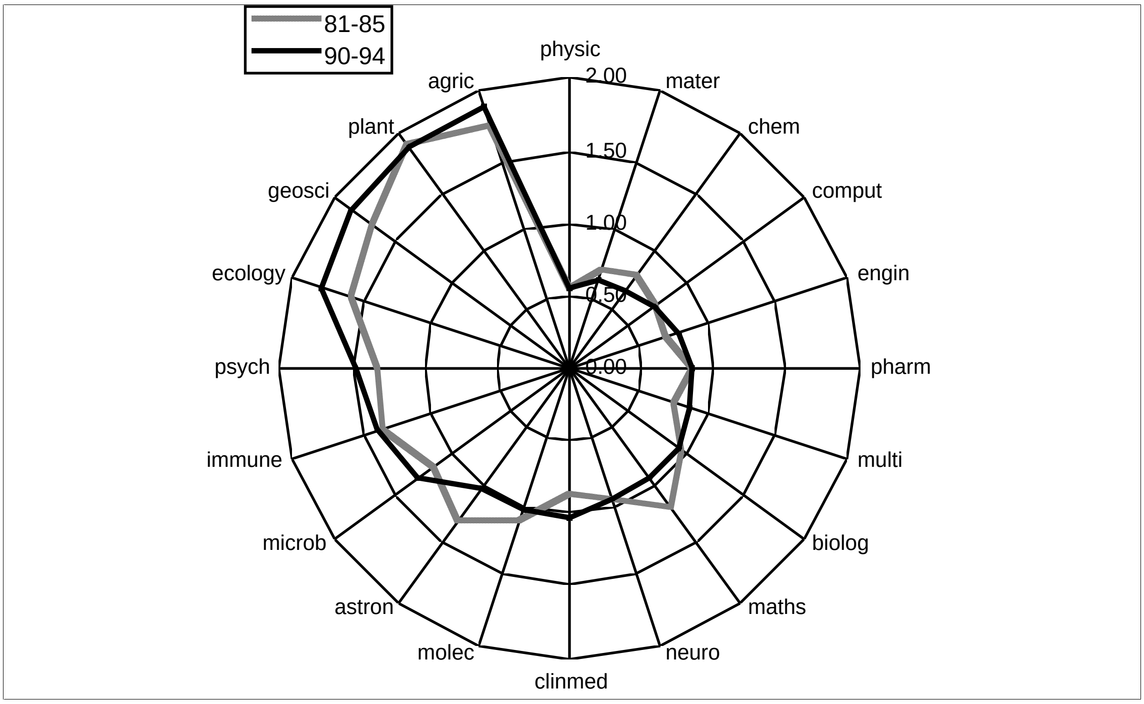
$$\Delta FS_{ij} = \left(P_{ijt} \big/ (\Sigma_{j=1}^{k} P_{ijt}) - P_{ijt-1} \big/ (\Sigma_{j=1}^{k} P_{ijt-1}) \right) - \left(\Sigma_{i=1}^{N} P_{ijt} \big/ (\Sigma_{i=1}^{N} \Sigma_{j=1}^{k} P_{ijt}) - \Sigma_{i=1}^{N} P_{ijt-1} \big/ (\Sigma_{i=1}^{N} \Sigma_{j=1}^{k} P_{ijt-1}) \right)$$

and then the field with the biggest value of ΔFS was identified. The field mnemonics are described in appendix C. **c** The field with the smallest value of ΔFS was identified.

Source: ISI database.

Agricultural science, geoscience, ecology/environment and psychology/psychiatry have all faced increasing degrees of RCA. Clinical medicine has shifted from a position where it was proportionately under-represented in Australian science to one where it now matches the situation globally. In contrast, astronomy, maths and chemistry have declined in relative importance.

Figure 4.11 Changes in revealed comparative advantage in Australia, 1981-85 to 1990-94 [a]



a The graph shows the revealed comparative advantage index discussed in chapter 2 for each field for 1981-85 and 1990-94.

Source: ISI database.

We have already noted that differences between countries in the structure of science can bias *relative* measures of performance. Differences over time can also have this effect. Accordingly we measured Australia's relative citation impact using a fixed set of weights (table 4.8). This has very little effect on our story – with Australian relative citation rates still declining steadily. It is true, however, that structural change has slightly exaggerated the real extent of the decline.

In chapter 2 we looked at a static picture of the consistency in quality across fields and the degree of specialisation. But are there any trends in performance over time? We need to be careful interpreting such trends. Over time a country may show a greater degree of variation in quality across fields simply because one or two fields *improved* in quality, while the rest remained at their older levels of quality. Similarly, a country may show a lower degree of variation in quality across fields if one or two 'star' fields fade in quality. Accordingly we look at the change in relative quality as well as changes in the evenness of quality.

Table 4.8 The effect of structural change in Australian science on relative citation impact [a]

	Variable weight RCI	*Fixed weight FWRCI*	*Variable weight index form 1981-85=100*	*Fixed weight index form 1981-85=100*
81-85	0.957	0.957	100.0	100.0
82-86	0.958	0.958	100.1	100.1
83-87	0.962	0.963	100.5	100.6
84-88	0.961	0.962	100.5	100.6
85-89	0.972	0.972	101.5	101.5
86-90	0.969	0.971	101.2	101.5
87-91	0.949	0.952	99.1	99.5
88-92	0.940	0.943	98.2	98.5
89-93	0.896	0.902	93.7	94.3
90-94	0.867	0.878	90.5	91.7

a The relative citation impact (RCI) and fixed weight relative citation impact (FWRCI) are defined as follows where C and P are citations and papers respectively:

$$RCI_t = \frac{\sum_{j=1}^{K} C_{AUST,t,j}}{\sum_{j=1}^{K} P_{AUST,t,j}} \Bigg/ \frac{\sum_{j=1}^{K} C_{WORLD,t,j}}{\sum_{j=1}^{K} P_{WORLD,t,j}}$$

$$FWRCI_t = \left(\sum_{j=1}^{K} \frac{P_{AUST,81-85,j}}{(\sum_{j=1}^{K} P_{AUST,81-85,j})} \times \frac{C_{AUST,t,j}}{P_{AUST,t,j}}\right) \Bigg/ \left(\sum_{j=1}^{K} \frac{P_{WORLD,81-85,j}}{(\sum_{j=1}^{K} P_{WORLD,81-85,j})} \times \frac{C_{WORLD,t,j}}{P_{WORLD,t,j}}\right)$$

Source: ISI database.

In Australia, as in all of the developed scientific countries, the changes are very slight (table 4.9). There has been a very small increase in specialisation and a tiny reduction in the amount of variation in quality across fields. The big changes are most apparent for the developing economies – with dramatically increasing consistency for Mexico, China, South Korea and Taiwan (though in the latter two cases this has been associated with a *fall* in overall quality). Surprisingly, most of the developing countries (except China and Indonesia) have tended to specialise more rather than less as their science systems have evolved. It does not appear that Australia's position as one of the most well rounded scientific societies in the APEC region will be challenged quickly.

4.6 Basic scientific proclivity over time

In chapter 2 we looked at a static picture of the scientific proclivity of Australia relative to other countries. Here we present a brief dynamic picture (table 4.10).

Table 4.9 Changes in the consistency and specialisation of science, 1981-85 to 1990-94 [a]

	Unevenness	*Specialisation*	*Change in relative quality*
Australia	-0.002	0.039	-0.099
Canada	-0.004	0.009	0.019
Chile	-0.026	0.480	-0.107
Denmark	0.009	-0.024	-0.089
Finland	0.002	-0.060	0.053
France	-0.025	-0.056	0.061
Germany	-0.009	-0.037	0.081
Hong Kong	0.000	-0.023	-0.043
India	-0.023	-0.007	-0.027
Indonesia	-0.167	-0.117	0.044
Italy	-0.014	-0.033	0.051
Japan	0.038	-0.033	-0.007
Malaysia	0.396	0.060	-0.005
Mexico	-0.470	0.148	-0.226
Netherlands	-0.023	-0.053	0.004
New Zealand	-0.015	-0.010	0.137
Norway	0.086	0.025	-0.071
Papua New Guinea	3.266	0.199	0.505
Peoples R. China	-0.703	-1.485	0.381
Philippines	0.568	0.736	0.216
Singapore	-0.009	0.557	0.387
South Africa	0.048	0.349	-0.023
South Korea	-0.223	0.016	-0.200
Sweden	0.003	-0.093	-0.078
Switzerland	-0.008	-0.041	-0.025
Taiwan	-0.431	0.327	-0.098
Thailand	-0.283	0.269	0.371
UK	-0.004	0.004	-0.009
US	-0.085	-0.020	0.009

a Specialisation and unevenness of quality (consistency) by field are defined in chapter 2. Here we simply take the numerical difference between these measures for two periods: 1981-1985 and 1990-94. The change in relative quality is measured as:

$$\Delta IMP_i = log\left(\sum_{j=1}^{K} C_{i,j,90-95} / \sum_{j=1}^{K} P_{i,j,90-95}\right) \Bigg/ \left(\sum_{i=1}^{N}\sum_{j=1}^{K} C_{i,j,90-95} / \sum_{i=1}^{N}\sum_{j=1}^{K} P_{i,j,90-95}\right)$$

$$- log\left(\sum_{j=1}^{K} C_{i,j,81-85} / \sum_{j=1}^{K} P_{i,j,81-85}\right) \Bigg/ \left(\sum_{i=1}^{N}\sum_{j=1}^{K} C_{i,j,81-85} / \sum_{i=1}^{N}\sum_{j=1}^{K} P_{i,j,81-85}\right)$$

Table 4.10 Papers per population and GDP over time

	Papers per 1000 people 1981	*Index of papers per person 1981*	*Trend 1981 to 1993*	*Papers per $billion US 1981*	*Index of papers per GDP 1981*	*Trend 1981 to 1993*	*Papers per 1000 people 1993*	*Index of papers per person 1993*	*Papers per $billion US 1993*	*Index of papers per GDP 1993*
Australia	0.704	100.0	0.017	47.8	100.0	0.029	0.854	100.0	67.1	100.0
Austria	0.365	51.8	0.036	34.5	72.1	0.007	0.540	63.2	36.9	54.9
Belgium	0.433	61.5	0.036	36.8	76.9	0.010	0.661	77.4	43.7	65.1
Canada	0.800	113.7	0.028	52.1	108.9	0.018	1.075	125.9	67.6	100.7
Denmark	0.751	106.7	0.030	60.7	126.9	0.015	1.074	125.7	70.6	105.2
Finland	0.548	77.8	0.040	43.3	90.7	0.053	0.964	112.9	95.2	141.9
France	0.428	60.9	0.034	30.7	64.2	0.026	0.621	72.7	43.4	64.7
Germany	0.554	78.7	0.005	48.4	101.2	-0.023	0.569	66.6	37.1	55.3
Greece	0.100	14.2	0.080	9.5	19.8	0.195	0.247	28.9	102.1	152.2
Iceland	0.190	27.1	0.100	4.0	8.4	0.275	0.740	86.7	159.6	237.9
Ireland	0.387	55.1	0.039	45.6	95.5	0.004	0.631	73.8	51.8	77.2
Italy	0.171	24.3	0.064	11.9	25.0	0.084	0.362	42.4	35.7	53.2
Japan	0.231	32.9	0.052	23.7	49.6	-0.004	0.416	48.7	22.9	34.2
Mexico	0.013	1.8	0.051	na	na	na	0.024	2.8	na	na
Netherlands	0.510	72.4	0.055	47.0	98.3	0.014	0.962	112.7	57.1	85.1
New Zealand	0.696	98.9	0.016	51.6	108.0	0.051	0.832	97.4	84.8	126.4
Norway	0.563	80.0	0.028	38.6	80.7	0.044	0.817	95.7	64.1	95.5
Portugal	0.024	3.4	0.138	2.5	5.1	0.209	0.121	14.2	31.8	47.4
Spain	0.092	13.0	0.104	9.7	20.3	0.113	0.329	38.5	42.7	63.7
Sweden	0.833	118.3	0.033	57.9	121.1	0.059	1.297	151.9	132.1	196.8
Switzerland	0.960	136.4	0.034	67.3	140.9	0.015	1.471	172.2	87.7	130.7
Turkey	0.007	1.0	0.120	0.7	1.4	0.442	0.027	3.2	103.5	154.2
UK	0.678	96.3	0.024	62.9	131.6	0.022	0.912	106.7	84.8	126.3
US	0.750	106.5	0.017	47.9	100.2	-0.001	0.886	103.8	47.4	70.6
India	0.020	2.8	-0.012	21.6	45.2	-0.001	0.016	1.9	20.0	29.8
Singapore	0.081	11.6	0.136	10.5	21.9	0.072	0.452	53.0	25.8	38.5
South Korea	0.006	0.9	0.202	2.2	4.6	0.111	0.068	8.0	8.2	12.2
Taiwan	0.029	4.2	0.182	6.5	13.5	0.105	0.225	26.4	21.1	31.5
Malaysia	0.016	2.3	0.025	0.0	0.1	0.368	0.023	2.7	3.2	4.8
Indonesia	0.001	0.1	0.053	0.3	0.6	0.080	0.001	0.1	0.8	1.2
PR China	0.001	0.2	0.135	1.1	2.4	0.055	0.007	0.9	1.9	2.8

Sources: The bibliometric data are from the ISI database. The remaining data are from the OECD.

Scientific papers per person in Australia have increased at a trend rate of around 1.7 per cent per annum from 1981 to 1993. This places Australia in 27th ranking among the 31 countries in table 4.10 – but in line with the moderate rates of growth achieved by other scientifically advanced countries like the US, Germany and the UK. Countries with fastest growing scientific proclivities are, not surprisingly, those with a less developed base – such as South Korea (20 per cent per annum), Taiwan (18.2 per cent) and China (13.5 per cent per annum).

But if we turn to papers published for each dollar of real GDP a different picture emerges. The growth in scientific papers in Australia has outstripped real GDP growth

– with papers per GDP increasing at a trend rate of nearly 3 per cent per annum.[10] This is much higher than for most other scientifically advanced countries. Given our income, Australians are making an increasingly greater contribution to science.

While the overall picture is of increasing scientific proclivity in Australia, actual papers per research scientist and engineer have fallen (figure 4.12). This is not an anomalous result as most other scientifically advanced countries have also shown a decrease – although the decline is particularly pronounced in Australia. The decline may reflect:

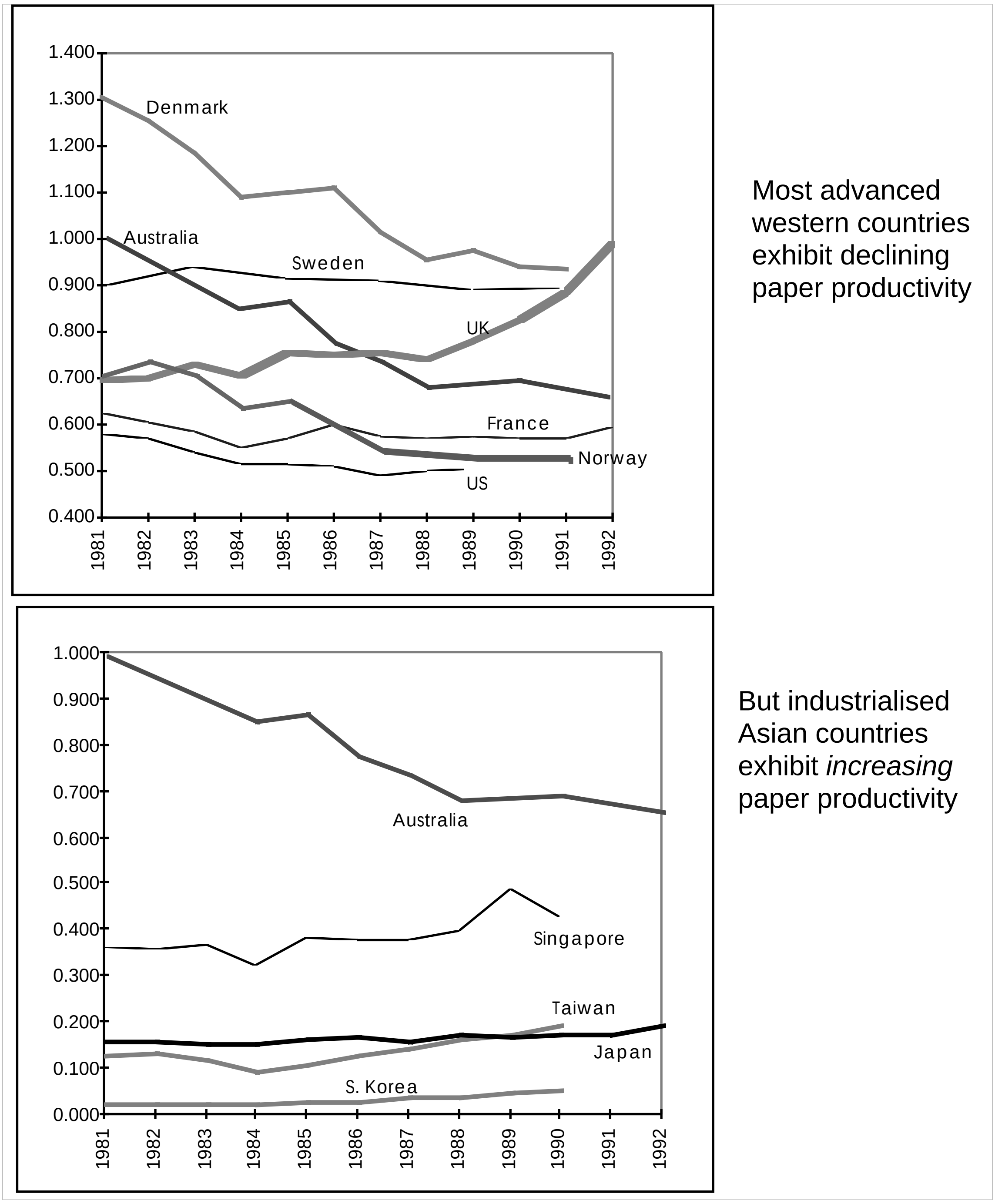
- lower publication rates for the large group of new academics who have joined the system over the period; and/or
- a shift from papers to other scientific and technological outputs. In this context it should be emphasised that an increasing proportion of Australia's engineers and scientists are engaged in research in industry – where papers are less frequently an output.

It is notable that the industrialised Asian countries show generally increasing paper productivity - a shift which we think represents both a movement of scientific resources towards basic research and the increasing quality of those resources. The other conspicuous feature of figure 4.11 is that notwithstanding the sharp decline in paper productivity in Australia, it still remains high by comparison with countries like the US, Japan, and the newly industrialising countries. [11]

[10] Note that the GDP measure is in real PPP $US, not in real Australian dollars. We use PPP adjusted GDP figures because we are trying to measure the income of different countries over time on a comparable basis. But PPP measures can have large errors. We also looked at the trend rate of growth in Australian papers per dollar of GDP (in real Australian dollars) and this was close to zero. The PPP results may still be right, but it is important to understand that it is the influence of the PPP index which drives this result.

[11] Though we emphasise that paper productivity is only a partial measure. It is clear that much of the scientific human capital in Japan and the NICs is not devoted to the sort of research which produces papers in scientific journals.

Figure 4.12 Index of ISI papers per research scientist and engineer (Australia 1981 figures =100.0), 1981 to 1992



Source: Data for research scientists and engineers from BIE (1996) and publications data from the ISI database.

Appendix A The use and abuse of bibliometrics

The use of bibliometrics – the statistical analysis of published research papers – has a long heritage as a performance indicator. The National Science Foundation has used such indicators since the 1970s. These indicators have gained, a sometimes grudging, acceptance as one of a suite of tools for looking at basic research. As noted in chapter one and two, such indicators have limitations:

- These particularly stem from the bias of the major index (the ISI) towards Roman scripts (Carpenter and Nairn 1981) and English language journals (Walley, 1986).[1] There is an additional bias towards early citation of English papers. Thus the latest year of the ISI database point to an increase in Australia's relative citation performance – but this evaporates when the ISI releases revised data a year later (figure A1.1).

- High search costs imply that there will be 'hysteresis' in citations – the renowned receive continued citations, while quality papers by less known authors may take longer to be discovered.

- Technical papers and recipes can be cited thousands of times, though they embody little frontier science. On the other hand, since these are clearly of wide application and usefulness to practising scientists, why should their value not be represented in citation indexes?

- It is sometimes argued that scientists in the US take a very insular view of the discipline and tend to give publications by their own nationals first preference. For example, Wood (1989) argues that the top US journals are reluctant to publish the results of research based on Australian material because of its

[1] For example, NBEET (1993) found a significant difference between Australia's share of world chemistry publications using the Chemical Abstracts Service (CAS), a wide ranging abstract service, and the Science Citation Index (SCI). Australia accounts for 1 per cent of world chemistry literature using CAS and 1.6 per cent using the SCI. NBEET interpret the difference as a bias due to language and script – but of course, other factors, such as differences in the classification of research, might also account for some of the differences. As well, it is possible that the SCI is more discriminating in its choice of journal set – a smaller journal set is not necessarily a worse one for making performance comparisons.

perceived limited international applications. This should not bias relative citation impacts *over time*. NBEET (1994) indicate the extent to which the ISI database covers Australian published papers satisfactorily – their view is that it does for most scientific fields.

Figure A.1 Bias in the last year data for Australian relative citation impacts[a]

a The ISI database was amended between 1993 and 1994 to include some additional fields. This is not likely to affect the relative measure.

Source: ISI databases for 1993 and 1994.

- 'Self citation' may bias some results. Self-citation is when an author cites his or her own research. At least 10 per cent of all citations are self citations (Garfield 1979). When performance assessments of individual scientists or university departments are based on citation analysis, this may create a route for artificial inflation of citation counts. On the other hand, self-citation is appropriate in many cases since science is a highly specialised discipline which builds on past findings.

- Citation circles. This resembles self citation except that authors cite the work of other authors in the group. This too may give skewed results from citation analysis. But it is difficult to draw the distinction between citation circles and loose affiliations of researchers who share a common interest in a subject matter, and therefore legitimately cite each other's research. It is hard to imagine that these behaviours would substantially distort the datasets.

- The obliteration phenomenon. This occurs when a particularly fundamental piece of research becomes so well known that scientists fail to cite it. Associated with this is when a review article is cited instead of the body of original research it encompasses.

- Inaccurate articles can draw many citations. Should such papers be accorded a high weight? On the one hand, a paper that is ‘right’ and highly cited seems more deserving of a higher weight that one which is wrong – and which attracts numerous citations through the process of refutation. On the other hand, papers which are ‘wrong’ (but clearly good enough to get published in a peer reviewed journal) can lead to whole new insights and developments in science.

- Raw citations and publication measures ignore the prestige of the journal. Arguably, a citation in a prestigious journal should receive a higher weight than one in a less prestigious journal. The fundamental difficulty here is that it is hard to objectively measure journal prestige and then to assign quantitative weights to publications or citations that reflect this prestige.

- Errors in interpretation can arise if analysts of bibliometrics do not acknowledge variations among disciplines.

- There are several ways of counting authors of collaborative articles. For instance, Martin (1994) differentiates among three methods of counting citations of such multi-author articles – first author, all authors, or fractionated counts (when each author receives a count equal to the article divided by the number of authors). Under 'all author' counts a single paper may be counted as an entry many times for many countries (as used in this report). The data from Bourke and Butler (1994) suggest different counting methods have little impact. Similarly, for the UK, Martin finds that most methodologies still produce the same qualitative results.

- Double counting can occur in other ways. For example, a paper may be allocated to more than one field – so that totals of papers across fields exceed the real total. There are a variety of means of dealing with this – in this report we use the incorrectly inflated total – so that field shares add to unity. Otherwise it is hard to interpret shares at all.

- Editorial practices may affect citation rates, for example, a page limitation on the amount of references allowed.

- The journal set used in the analysis can expand over time. This can give the spurious impression of growing publication counts. This affects the analysis conducted in the main text of this report since the ISI database used is not based on a fixed journal set. We checked the degree to which this mattered for the last few years. We compared results of the 1993 ISI dataset with those of the 1994 dataset for a common year, 1993. With a fixed journal set the number of publications should stay fixed for 1993, regardless of when the data are collected. We find that (for a fixed group of fields between the two datasets[2]) journal inflation has a small impact on Australian publications counts. The ISI 1994 dataset suggests growth in Australian scientific publications (excluding psychology) of 3.5 per cent in 1993 and 7.8 per cent in 1994. The difference between the 1994 and the 1993 database counts of publications for 1993 is only 1.1 per cent. So most of the growth recorded in publications appears to be genuine, rather than a product of a varying journal set. As well, journal inflation should not generally matter when *relative* comparisons are being made – but readers should note possible problems when they look at the material on changes in paper productivity in chapter 4. Martin et al (1990) finds that the UK

[2] The ISI not only expanded the journal set in 1994 – but also introduced some field changes, including the addition of psychology/psychiatry and some social sciences. We have excluded social sciences from any of the analysis reported in this report – but do include psychology/psychiatry. For the purpose of this comparison, this field had to be removed.

publication share data do not appear grossly affected by a dynamic rather than a constant journal set. It is possible, though, that measurement of Australia’s relative performance over the 1980s might have been adversely affected by the greater introduction into the ISI database of non-English journals. This would correct a past bias against foreign language journals. In this case, Australia’s relative citation performance in the past would have been biased up, while more recent measures would have been less biased – leading to a potentially spurious drop in relative performance over time. As noted in the main text, it is worth finding out if there has been a change in the nature of new journals introduced to the ISI database.

- Lowly or zero cited papers may be ‘ahead of the times’ rather than low quality.
- All sorts of modes of communication of significant research – from working papers, physical prototypes of scientific equipment, computer programs, and seminar papers are not counted as publications in the main publication indexes.
- There are many other outputs of scientists – such as teaching, advice to government, non-published research for commercial purposes, scientific services (such as meteorological services) which are not counted as outputs using bibliometrics. Bibliometric measures are necessarily partial.
- Time lag errors. Citation counts take time to accumulate. This can lead to biases (see appendix 4 for more details).
- Publication counts can multiply as authors put slight elaborations of the same material into many journals or break up a substantial article into several more minor ones.
- Citation rates certainly measure visibility – but do they measure quality as well? The view taken in this report is that while we can imagine circumstances where citation rates measure only visibility, that on average they do correlate with quality too. We view a high relative citation impact as an indicator of the quality of that body of knowledge. Of course, small *changes* in relative citation impacts over a few years may not reflect quality changes – but either statistical ‘noise’ or changes in visibility not correlated with quality.

Nevertheless, despite this litany of difficulties, there is probably no better data source for objective measurement of basic scientific performance between countries.

Appendix B Formulas

We list the major formulas used in manipulating the ISI database here.

1 CP_{ij} is the number of papers in the ith country and jth field which are cited at least once.

2 C_{ij} is the number of citations in the ith country and jth field.

3 P_{ij} is the number of papers in the ith country and jth field.

4 *Share cited* is the ratio of papers which are cited at least once (CP) to total papers (P) or $Share\ cited_i = \left(\sum_{j=1}^{k} CP_{ij} / \sum_{j=1}^{k} P_{ij}\right)$ where there are k fields.

5 *Citation impact* is the number of citations (C) per paper: $Citation\ impact_i = \left(\sum_{j=1}^{k} C_{ij} / \sum_{j=1}^{k} P_{ij}\right)$ where there are k fields

6 *Relative citation impact* (IMP) is the ratio of the share of world citations to the share of world publications. It can be calculated for a whole country or for just one field of one country. For example, IMP for a whole country is defined as:

$$IMP_i = \left(\sum_{j=1}^{k} C_{ij} / \sum_{i=1}^{N} \sum_{j=1}^{k} C_{ij}\right) / \left(\sum_{j=1}^{k} P_{ij} / \sum_{i=1}^{N} \sum_{j=1}^{k} P_{ij}\right)$$ or

$$\left(\sum_{j=1}^{k} C_{ij} / \sum_{j=1}^{k} P_{ij}\right) / \left(\sum_{i=1}^{N} \sum_{j=1}^{k} C_{ij} / \sum_{i=1}^{N} \sum_{j=1}^{k} P_{ij}\right)$$

where there are N countries and k fields.

7 *Relative cited* (REL) is the ratio of the share of world papers which are cited at least once to the world share of publications. It can be formed for a whole country or a particular field. For a whole country, the measure is:

$$REL_i = \left(\sum_{j=1}^{k} CP_{ij} / \sum_{j=1}^{k} P_{ij}\right) / \left(\sum_{i=1}^{N} \sum_{j=1}^{k} CP_{ij} / \sum_{i=1}^{N} \sum_{j=1}^{k} P_{ij}\right)$$ where there are N countries and k fields.

8 Share of Australian papers in the jth field is $APSH_{AUST,j} = P_{AUST,j} / \left(\sum_{j=1}^{k} P_{AUST,j}\right)$ where there are k fields.

9 Share of Australian citations in a given field: $CSH_{AUST,j} = C_{AUST,j} / \left(\sum_{j=1}^{k} C_{AUST,j}\right)$.

10 The world publication share in the ith country and jth field is $PSH_{ij} = P_{ij} / \left(\sum_{i=1}^{N} P_{ij}\right)$.

11 The world citation share in the ith country and jth field is $CSH_{ij} = C_{ij} / \sum_{i=1}^{N} C_{ij}$.

12 The measure of comparative advantage we are using here is:

$$RCA_{i,j} = (P_{i,j} / \Sigma_{i=1}^{N} P_{i,j}) \Big/ \left(\Sigma_{j=1}^{k} P_{i,j} / \Sigma_{j=1}^{N} \Sigma_{j=1}^{k} P_{i,j}\right) = (P_{i,j} / \Sigma_{j=1}^{k} P_{i,j}) \Big/ \left(\Sigma_{i=1}^{N} P_{i,j} / \Sigma_{j=1}^{N} \Sigma_{j=1}^{k} P_{i,j}\right)$$

13 The score of the intensity of collaboration by discipline is:

$SCORE_{ij} = \{ COLL_{ij} \Big/ \sum_{j=1}^{k} COLL_{ij} \} \Big/ (\sum_{i=1}^{N} COLL_{ij} \Big/ \sum_{j=1}^{k} \sum_{i=1}^{N} COLL_{ij})$ where $COLL_{ij}$ is the number of collaborative papers by country i with Australia in field j.

14 The strength of collaborative links are $LINK_{iq} = (COLL_{iq} / COLL_i) / \{ COLL_q / TCOLL \}$ where $COLL_{iq}$ is the number of collaborative papers of country i with country q, $COLL_i$ is the number of collaborative papers of country i with all other countries in the region and $TCOLL$ is the total number of collaborative papers in the region.

15 The change in field shares (relative to the world) was calculated for each country and field:

$$\Delta FS_{ij} = \left(P_{ijt} \Big/ (\sum_{j=1}^{k} P_{ijt}) - P_{ijt-1} \Big/ (\sum_{j=1}^{k} P_{ijt-1})\right)$$
$$- \left(\sum_{i=1}^{N} P_{ijt} \Big/ (\sum_{i=1}^{N} \sum_{j=1}^{k} P_{ijt}) - \sum_{i=1}^{N} P_{ijt-1} \Big/ (\sum_{i=1}^{N} \sum_{j=1}^{k} P_{ijt-1})\right)$$

and then the field with the biggest value of ΔFS was identified.

16 The relative citation impact (RCI) and fixed weight relative citation impact (FWRCI) are defined as follows where C and P are citations and papers respectively:

$$RCI_t = \frac{\Sigma_{j=1}^{K} C_{AUST,t,j}}{\Sigma_{j=1}^{K} P_{AUST,t,j}} \Bigg/ \frac{\Sigma_{j=1}^{K} C_{WORLD,t,j}}{\Sigma_{j=1}^{K} P_{WORLD,t,j}}$$

$$FWRCI_t = \left(\sum_{j=1}^{K} \frac{P_{AUST,81-85,j}}{(\Sigma_{j=1}^{K} P_{AUST,81-85,j})} \times \frac{C_{AUST,t,j}}{P_{AUST,t,j}} \right) \Bigg/ \left(\sum_{j=1}^{K} \frac{P_{WORLD,81-85,j}}{(\Sigma_{j=1}^{K} P_{WORLD,81-85,j})} \times \frac{C_{WORLD,t,j}}{P_{WORLD,t,j}} \right)$$

17 The change in relative quality is measured as:

$$\Delta IMP_i = log\left(\sum_{j=1}^{K} C_{i,j,90-95} / \sum_{j=1}^{K} P_{i,j,90-95} \right) \Bigg/ \left(\sum_{i=1}^{N} \sum_{j=1}^{K} C_{i,j,90-95} / \sum_{i=1}^{N} \sum_{j=1}^{K} P_{i,j,90-95} \right)$$
$$- log\left(\sum_{j=1}^{K} C_{i,j,81-85} / \sum_{j=1}^{K} P_{i,j,81-85} \right) \Bigg/ \left(\sum_{i=1}^{N} \sum_{j=1}^{K} C_{i,j,81-85} / \sum_{i=1}^{N} \sum_{j=1}^{K} P_{i,j,81-85} \right)$$

Appendix C Bibliometric statistics

The data were obtained by manipulating the ISI database for 1994. Some journal articles are written by authors from different countries. Each of these is recorded as an article attributed to a country. Thus the total number of papers exceeds the real world total – but we use the inflated total so that any shares add to one. We did not use the full set of ISI fields in computing the above statistics, but compiled data for 20 scientific fields (table C.1). The following fields were excluded: Economics and business, Education, and Social Sciences. Accordingly, the data recorded here and in the main text will **not** match ISI totals.

Table C.1 Fields in the database

Field description	*Field mnemonic*
Agricultural Sciences	agric
Astrophysics	astron
Biology & Biochemistry	biolog
Chemistry	chem
Clinical Medicine	clinmed
Computer Science	comput
Ecology and the environment	ecology
Engineering	engin
Geosciences	geosci
Immunology	immune
Materials Science	mater
Mathematics	maths
Microbiology	microb
Molecular biology & Genetics	molec
Multidisciplinary	multi
Neuroscience	neuro
Pharmacology	pharm
Physics	physic
Plant & Animal Science	plant
Psychology/psychiatry	psych
All fields	all

Table C.2 Share of world papers[a] by field, 1981-1994 (selected countries)[b]

	agric	*astron*	*biolog*	*chem*	*clinmed*	*comput*	*ecology*	*engin*	*geosci*	*immune*
Australia	3.93	2.53	2.04	1.53	2.01	1.53	3.62	1.57	3.88	2.95
Canada	4.37	4.08	4.48	3.39	3.90	5.46	7.43	4.62	8.23	3.68
Chile	0.26	1.16	0.17	0.16	0.22	0.08	0.26	0.04	0.11	0.06
Denmark	0.53	0.61	1.13	0.47	1.43	0.44	0.86	0.39	0.54	1.05
Finland	0.75	0.51	0.79	0.37	1.10	0.66	0.83	0.41	0.33	0.89
France	3.61	5.23	5.20	5.32	5.58	3.72	2.89	3.55	5.92	5.74
Germany	7.39	7.78	5.55	8.96	7.26	6.28	4.97	6.88	4.81	5.33
Hong Kong	0.03	0.06	0.13	0.12	0.26	0.30	0.17	0.26	0.05	0.11
India	6.56	2.35	1.71	4.13	0.55	1.47	3.34	3.00	2.54	0.53
Indonesia	0.09	0.04	0.02	0.01	0.02	0.00	0.08	0.02	0.08	0.03
Italy	1.69	4.49	3.14	3.14	2.99	3.31	1.49	2.27	1.66	2.89
Japan	10.00	3.34	9.01	10.22	4.23	5.44	3.18	8.46	3.02	7.08
Malaysia	0.17	0.01	0.05	0.06	0.05	0.02	0.12	0.04	0.04	0.03
Mexico	0.47	0.68	0.19	0.18	0.24	0.06	0.37	0.15	0.25	0.15
Netherlands	1.50	2.71	2.32	1.67	2.03	1.95	2.27	1.54	1.47	3.26
New Zealand	1.52	0.25	0.40	0.26	0.45	0.22	0.92	0.23	0.97	0.19
Norway	0.38	0.29	0.62	0.34	0.70	0.32	0.89	0.32	1.08	0.87
PNG	0.04	0.00	0.02	0.00	0.04	0.00	0.03	0.01	0.03	0.03
P.R. China	0.38	0.78	0.27	1.21	0.36	0.76	0.50	1.52	1.41	0.17
Philippines	0.28	0.00	0.03	0.00	0.03	0.00	0.15	0.01	0.03	0.04
Singapore	0.05	0.01	0.08	0.10	0.11	0.45	0.12	0.38	0.04	0.06
S. Africa	0.36	0.74	0.34	0.36	0.72	0.25	1.02	0.29	0.92	0.24
S. Korea	0.14	0.12	0.13	0.48	0.09	0.51	0.11	0.55	0.09	0.07
Sweden	0.97	0.94	2.31	1.11	2.55	1.11	2.33	0.93	1.01	2.92
Switzerland	0.66	0.87	1.41	1.31	1.70	1.05	0.83	1.11	1.08	2.44
Taiwan	0.45	0.06	0.23	0.50	0.25	1.20	0.25	1.09	0.13	0.17
Thailand	0.19	0.00	0.07	0.03	0.15	0.04	0.18	0.09	0.04	0.17
UK	6.14	8.55	8.32	6.53	10.10	8.61	6.93	8.55	8.50	9.13
US	30.76	36.54	37.62	22.79	39.25	45.25	43.19	38.37	35.95	41.75
Africa & M.East	3.58	1.11	2.07	2.05	2.31	2.37	3.09	2.43	1.93	2.07
C&S America	3.28	1.71	1.51	0.90	0.65	0.45	1.24	0.62	0.85	0.90
Rest of world	9.46	12.43	8.67	22.31	8.66	6.69	6.35	10.31	13.00	5.01
APEC	53.13	49.67	54.93	41.05	51.68	61.34	60.67	57.41	54.35	56.73
TOTAL	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0

Continued overleaf

Table C.2 continued

	mater	*maths*	*microb*	*molec*	*multi*	*neuro*	*pharm*	*physic*	*plant*	*psych*	*all*
Australia	1.42	2.24	2.59	2.25	1.73	2.05	1.85	1.15	4.03	2.98	2.14
Canada	3.80	5.30	4.33	4.24	1.90	6.24	4.10	2.81	7.35	7.77	4.47
Chile	0.07	0.18	0.12	0.10	0.08	0.12	0.16	0.08	0.24	0.05	0.16
Denmark	0.25	0.61	1.34	0.87	0.27	0.98	0.96	0.66	0.74	0.38	0.84
Finland	0.61	0.49	0.82	0.80	0.20	0.89	0.87	0.42	0.61	0.40	0.67
France	4.38	7.49	4.95	6.42	9.91	4.77	4.78	6.31	4.17	1.22	5.15
Germany	9.09	7.90	7.75	7.26	3.23	5.14	7.42	8.43	6.62	4.08	7.04
Hong Kong	0.10	0.19	0.10	0.18	0.08	0.12	0.18	0.10	0.07	0.25	0.15
India	4.17	2.38	1.84	0.75	7.33	0.36	1.59	2.98	4.27	0.38	2.43
Indonesia	0.01	0.01	0.04	0.01	0.04	0.00	0.02	0.01	0.08	0.01	0.03
Italy	1.45	2.93	2.15	2.85	0.94	3.27	4.78	3.17	1.32	0.86	2.72
Japan	12.15	4.60	7.10	6.32	1.57	5.89	13.32	9.40	5.41	1.33	7.27
Malaysia	0.05	0.04	0.06	0.03	0.05	0.01	0.05	0.02	0.14	0.02	0.05
Mexico	0.21	0.25	0.31	0.23	0.15	0.32	0.23	0.33	0.37	0.21	0.25
Netherlands	1.04	1.62	2.78	2.58	0.85	2.09	2.41	1.64	2.22	1.82	1.95
New Zealand	0.20	0.37	0.50	0.34	0.70	0.39	0.49	0.14	1.07	0.64	0.45
Norway	0.24	0.40	0.73	0.43	0.16	0.56	0.52	0.25	0.72	0.46	0.52
PNG	0.00	0.01	0.02	0.01	0.02	0.00	0.01	0.00	0.04	0.01	0.02
P.R. China	1.73	1.57	0.29	0.27	6.73	0.23	0.94	2.11	0.57	0.11	0.94
Philippines	0.01	0.01	0.04	0.03	0.12	0.01	0.02	0.01	0.17	0.02	0.04
Singapore	0.14	0.19	0.08	0.08	0.03	0.05	0.13	0.09	0.07	0.06	0.11
S. Africa	0.37	0.37	0.48	0.22	1.24	0.12	0.26	0.24	1.54	0.27	0.51
S. Korea	0.75	0.24	0.22	0.07	0.03	0.05	0.16	0.49	0.08	0.04	0.25
Sweden	1.40	0.76	2.41	1.84	0.53	2.70	2.39	1.06	1.26	1.11	1.70
Switzerland	0.89	0.91	1.51	1.88	1.23	1.51	1.57	1.99	0.97	0.62	1.41
Taiwan	1.00	0.44	0.28	0.17	0.10	0.21	0.43	0.57	0.32	0.10	0.40
Thailand	0.02	0.01	0.16	0.05	0.26	0.02	0.11	0.01	0.11	0.02	0.08
UK	6.46	6.30	9.77	8.93	6.80	9.04	8.46	5.57	7.72	8.14	7.97
US	28.68	36.64	33.06	39.48	17.18	44.62	30.95	27.12	33.66	60.41	34.64
Africa & M.East	1.80	3.14	2.02	1.43	2.00	1.42	1.87	1.73	3.08	1.89	2.17
C&S America	0.64	1.14	1.36	1.15	1.15	0.78	0.85	1.31	1.39	0.31	1.07
Rest of world	16.87	11.28	10.80	8.72	33.41	6.06	8.11	19.80	9.58	4.03	12.36
APEC	50.35	52.29	49.30	53.87	30.76	60.33	53.16	44.44	53.79	74.02	51.47
TOTAL	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0

a Some papers are written jointly by authors from more than one country. Such papers are counted in each of the countries of the authors. In order that percentages add to one hundred we define the world total of papers as the sum of papers across all countries, even though this involves some double counting. **b** The measure here is the world share of papers for each country in each field (formula 10 in appendix B)

Source: ISI database.

Table C.3 Share of world citations by field, 1981-1994 (selected countries)[a]

	agric	*astron*	*biolog*	*chem*	*clinmed*	*comput*	*ecology*	*engin*	*geosci*	*immune*
Australia	4.80	2.70	1.83	1.89	1.95	1.28	4.07	1.82	4.51	2.54
Canada	5.96	4.01	4.20	4.39	4.39	5.91	7.74	4.55	7.10	3.04
Chile	0.24	1.32	0.07	0.09	0.07	0.03	0.13	0.02	0.07	0.04
Denmark	0.73	0.54	1.07	0.58	1.52	0.46	0.83	0.62	0.52	0.80
Finland	0.57	0.29	0.64	0.26	1.06	0.58	0.89	0.36	0.21	0.64
France	3.85	4.75	4.19	5.60	3.02	3.22	1.89	3.54	6.07	4.71
Germany	5.00	7.53	5.32	9.36	3.56	4.23	3.55	5.72	4.21	4.16
Hong Kong	0.02	0.03	0.06	0.10	0.15	0.14	0.06	0.13	0.02	0.04
India	2.07	0.62	0.38	1.67	0.19	0.73	1.11	1.30	0.73	0.18
Indonesia	0.05	0.02	0.01	0.00	0.02	0.00	0.03	0.01	0.05	0.02
Italy	1.24	3.28	1.90	2.94	2.17	2.06	0.96	1.94	1.04	1.82
Japan	10.74	2.52	6.79	9.61	2.99	3.13	1.95	7.54	2.28	4.50
Malaysia	0.13	0.00	0.01	0.03	0.02	0.01	0.06	0.02	0.01	0.01
Mexico	0.31	0.39	0.09	0.11	0.12	0.06	0.19	0.10	0.16	0.09
Netherlands	1.98	3.34	2.15	2.17	2.10	2.00	2.47	1.69	1.26	2.86
New Zealand	1.64	0.14	0.29	0.26	0.45	0.14	0.93	0.21	0.76	0.11
Norway	0.47	0.19	0.48	0.32	0.64	0.30	1.14	0.35	0.88	0.70
PNG	0.03	0.00	0.01	0.00	0.02	0.00	0.01	0.00	0.02	0.03
P.R. China	0.24	0.24	0.10	0.39	0.14	0.38	0.23	0.71	0.58	0.07
Philippines	0.27	0.00	0.02	0.00	0.02	0.00	0.10	0.01	0.01	0.03
Singapore	0.03	0.00	0.03	0.05	0.04	0.18	0.04	0.13	0.01	0.01
S. Africa	0.39	0.65	0.19	0.27	0.40	0.13	0.72	0.19	0.65	0.13
S. Korea	0.08	0.03	0.04	0.19	0.04	0.18	0.04	0.23	0.04	0.02
Sweden	1.88	0.94	2.54	1.44	2.77	0.86	3.27	1.26	0.83	2.59
Switzerland	0.79	1.17	1.91	2.00	1.39	1.24	0.93	1.35	1.21	3.29
Taiwan	0.22	0.02	0.09	0.22	0.14	0.44	0.12	0.55	0.06	0.05
Thailand	0.12	0.00	0.03	0.01	0.09	0.01	0.07	0.04	0.01	0.11
UK	9.58	9.68	8.77	7.94	11.12	5.92	7.22	8.37	9.61	8.79
US	38.53	49.21	51.37	37.12	54.79	59.70	53.70	50.29	51.46	53.54
Africa & M.East	2.27	0.71	1.26	1.48	1.20	2.54	1.83	1.68	1.09	1.45
C&S America	1.30	0.84	0.44	0.49	0.40	0.28	0.76	0.44	0.54	0.47
Rest of world	4.45	4.84	3.70	9.02	3.02	3.84	2.96	4.83	3.99	3.16
APEC	63.41	60.63	65.05	54.47	65.44	71.59	69.46	66.36	67.15	64.25
TOTAL	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0

Continued overleaf

Table C.3 continued

	mater	*maths*	*microb*	*molec*	*multi*	*neuro*	*pharm*	*physic*	*plant*	*psych*	*all*
Australia	1.56	2.35	2.21	1.65	1.88	1.78	1.96	0.95	4.88	2.38	2.07
Canada	3.70	5.04	3.88	3.37	3.17	5.89	4.59	2.67	8.70	7.76	4.48
Chile	0.04	0.12	0.04	0.03	0.10	0.05	0.08	0.04	0.14	0.02	0.09
Denmark	0.33	0.95	0.93	0.73	0.49	1.04	1.08	1.07	0.96	0.44	0.98
Finland	0.42	0.47	0.64	0.63	0.24	0.56	0.69	0.48	0.49	0.27	0.61
France	4.70	6.95	4.29	4.87	8.19	4.10	4.64	7.01	3.45	0.65	4.46
Germany	7.33	6.81	7.15	7.64	4.42	4.53	6.72	9.72	5.95	1.76	6.04
Hong Kong	0.05	0.13	0.04	0.06	0.07	0.06	0.09	0.04	0.05	0.13	0.08
India	2.49	0.93	0.43	0.15	1.72	0.11	0.51	1.17	0.97	0.12	0.65
Indonesia	0.00	0.00	0.03	0.00	0.03	0.00	0.00	0.00	0.04	0.01	0.01
Italy	1.35	2.42	1.04	1.55	1.17	1.99	3.31	2.82	0.92	0.61	2.05
Japan	11.27	3.34	5.17	3.86	2.12	3.86	8.95	8.14	4.27	0.37	5.68
Malaysia	0.03	0.03	0.02	0.01	0.03	0.00	0.02	0.01	0.07	0.01	0.02
Mexico	0.13	0.22	0.18	0.09	0.10	0.16	0.11	0.17	0.20	0.02	0.13
Netherlands	1.34	1.98	2.69	2.44	1.16	1.69	2.45	2.03	2.65	1.22	2.15
New Zealand	0.13	0.32	0.41	0.19	0.65	0.26	0.71	0.16	0.91	0.48	0.36
Norway	0.21	0.53	0.46	0.26	0.28	0.47	0.41	0.20	0.86	0.32	0.47
PNG	0.00	0.00	0.02	0.01	0.03	0.00	0.00	0.00	0.03	0.00	0.01
P.R. China	0.73	0.70	0.12	0.09	1.14	0.10	0.24	0.65	0.19	0.04	0.25
Philippines	0.00	0.00	0.02	0.01	0.05	0.02	0.00	0.00	0.11	0.01	0.02
Singapore	0.08	0.11	0.04	0.03	0.01	0.02	0.05	0.03	0.04	0.01	0.04
S. Africa	0.32	0.31	0.31	0.10	0.75	0.05	0.13	0.15	0.98	0.11	0.28
S. Korea	0.51	0.08	0.09	0.02	0.01	0.01	0.05	0.17	0.04	0.02	0.08
Sweden	1.50	0.86	1.98	1.61	0.94	3.30	3.00	1.20	1.70	1.26	2.10
Switzerland	1.05	0.94	1.73	2.88	2.27	1.80	2.37	3.30	1.03	0.32	1.94
Taiwan	0.55	0.27	0.14	0.06	0.07	0.07	0.17	0.18	0.14	0.03	0.14
Thailand	0.01	0.01	0.09	0.02	0.16	0.01	0.06	0.00	0.06	0.01	0.04
UK	7.28	7.95	9.95	9.37	9.77	10.19	11.59	6.08	10.74	9.06	9.13
US	45.64	45.72	49.86	53.63	44.18	53.48	40.19	40.10	42.40	70.05	49.03
Africa & M.East	1.28	2.64	1.32	1.17	1.26	0.92	0.82	1.51	2.02	1.06	1.33
C&S America	0.52	0.84	0.60	0.21	0.63	0.39	0.43	0.70	0.73	0.10	0.48
Rest of world	5.45	6.99	4.13	3.28	12.93	3.07	4.59	9.23	4.27	1.31	4.80
APEC	64.43	58.43	62.37	63.11	53.78	65.79	57.27	53.33	62.28	81.38	62.53
TOTAL	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0

a See note a in table C.2. The measure here is the world share of citations for country j in a given field. (formula 11 in appendix B).

Source: ISI database.

Table C.4 Relative citation rate per paper by field, 1981-1994 (selected countries) [a]

	agric	*astron*	*biolog*	*chem*	*clinmed*	*comput*	*ecology*	*engin*	*geosci*	*immune*
Australia	1.22	1.07	0.90	1.24	0.97	0.84	1.12	1.16	1.16	0.86
Canada	1.36	0.98	0.94	1.30	1.12	1.08	1.04	0.98	0.86	0.83
Chile	0.92	1.14	0.43	0.55	0.31	0.40	0.50	0.54	0.63	0.66
Denmark	1.38	0.88	0.94	1.23	1.06	1.05	0.97	1.59	0.96	0.76
Finland	0.76	0.57	0.81	0.70	0.96	0.89	1.07	0.88	0.64	0.72
France	1.07	0.91	0.81	1.05	0.54	0.87	0.66	1.00	1.03	0.82
Germany	0.68	0.97	0.96	1.04	0.49	0.67	0.71	0.83	0.88	0.78
Hong Kong	0.60	0.46	0.48	0.80	0.58	0.45	0.37	0.49	0.37	0.37
India	0.32	0.26	0.22	0.40	0.35	0.50	0.33	0.43	0.29	0.34
Indonesia	0.58	0.48	0.40	0.37	0.82	0.15	0.33	0.50	0.55	0.73
Italy	0.73	0.73	0.60	0.94	0.73	0.62	0.65	0.85	0.63	0.63
Japan	1.07	0.75	0.75	0.94	0.71	0.58	0.61	0.89	0.75	0.64
Malaysia	0.77	0.15	0.26	0.52	0.36	0.51	0.48	0.44	0.41	0.41
Mexico	0.67	0.58	0.46	0.60	0.49	0.97	0.51	0.70	0.66	0.56
Netherlands	1.32	1.23	0.93	1.30	1.04	1.03	1.09	1.10	0.86	0.88
New Zealand	1.08	0.57	0.73	1.00	1.01	0.63	1.01	0.90	0.78	0.61
Norway	1.23	0.64	0.78	0.95	0.91	0.96	1.28	1.10	0.82	0.80
PNG	0.76	0.50	0.55	0.33	0.44	0.15	0.49	0.30	0.55	0.94
P.R. China	0.64	0.30	0.39	0.32	0.38	0.50	0.45	0.47	0.41	0.40
Philippines	0.99	0.11	0.82	0.82	0.74	0.91	0.67	0.50	0.47	0.81
Singapore	0.57	0.09	0.36	0.54	0.38	0.41	0.33	0.35	0.32	0.21
S. Africa	1.10	0.88	0.56	0.74	0.55	0.53	0.71	0.66	0.71	0.52
S. Korea	0.56	0.23	0.34	0.40	0.47	0.34	0.41	0.42	0.42	0.23
Sweden	1.93	1.01	1.10	1.30	1.09	0.78	1.40	1.35	0.82	0.89
Switzerland	1.21	1.35	1.36	1.53	0.82	1.18	1.12	1.22	1.13	1.35
Taiwan	0.48	0.30	0.39	0.44	0.57	0.37	0.47	0.51	0.44	0.29
Thailand	0.66	0.00	0.38	0.57	0.64	0.28	0.42	0.45	0.29	0.65
UK	1.56	1.13	1.05	1.21	1.10	0.69	1.04	0.98	1.13	0.96
US	1.25	1.35	1.37	1.63	1.40	1.32	1.24	1.31	1.43	1.28
Africa & M.East	0.63	0.63	0.61	0.72	0.52	1.07	0.59	0.69	0.57	0.70
C&S America	0.39	0.49	0.29	0.55	0.62	0.62	0.62	0.71	0.63	0.52
Rest of world	0.47	0.39	0.43	0.40	0.35	0.57	0.47	0.47	0.31	0.63
APEC	1.19	1.22	1.18	1.33	1.27	1.17	1.14	1.16	1.24	1.13
TOTAL	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00

Continued overleaf

Table C.4 continued

	mater	*maths*	*microb*	*molec*	*multi*	*neuro*	*pharm*	*physic*	*plant*	*psych*	*all*
Australia	1.10	1.05	0.86	0.73	1.09	0.87	1.06	0.83	1.21	0.80	0.97
Canada	0.97	0.95	0.90	0.79	1.67	0.94	1.12	0.95	1.18	1.00	1.00
Chile	0.59	0.66	0.37	0.33	1.19	0.46	0.52	0.60	0.57	0.50	0.55
Denmark	1.32	1.57	0.69	0.84	1.82	1.06	1.13	1.61	1.30	1.14	1.16
Finland	0.68	0.96	0.77	0.78	1.22	0.63	0.79	1.16	0.80	0.68	0.90
France	1.07	0.93	0.87	0.76	0.83	0.86	0.97	1.11	0.83	0.54	0.87
Germany	0.81	0.86	0.92	1.05	1.37	0.88	0.91	1.15	0.90	0.43	0.86
Hong Kong	0.54	0.71	0.43	0.30	0.89	0.50	0.48	0.38	0.70	0.53	0.51
India	0.60	0.39	0.24	0.20	0.23	0.31	0.32	0.39	0.23	0.31	0.27
Indonesia	0.33	0.13	0.68	0.21	0.80	0.18	0.13	0.19	0.52	1.10	0.47
Italy	0.93	0.83	0.48	0.55	1.25	0.61	0.69	0.89	0.70	0.70	0.75
Japan	0.93	0.73	0.73	0.61	1.34	0.66	0.67	0.87	0.79	0.28	0.78
Malaysia	0.54	0.67	0.39	0.42	0.56	0.32	0.30	0.28	0.48	0.29	0.35
Mexico	0.60	0.87	0.58	0.38	0.68	0.52	0.47	0.53	0.54	0.12	0.51
Netherlands	1.29	1.22	0.97	0.95	1.36	0.81	1.02	1.24	1.19	0.67	1.10
New Zealand	0.65	0.87	0.83	0.55	0.93	0.67	1.45	1.13	0.85	0.75	0.80
Norway	0.88	1.33	0.63	0.61	1.75	0.85	0.78	0.80	1.20	0.71	0.91
PNG	0.28	0.19	1.01	0.64	1.84	0.65	0.07	0.23	0.71	0.42	0.54
P.R. China	0.42	0.44	0.41	0.34	0.17	0.46	0.26	0.31	0.34	0.37	0.27
Philippines	0.16	0.17	0.65	0.31	0.43	2.91	0.29	0.40	0.64	0.38	0.58
Singapore	0.56	0.54	0.44	0.33	0.39	0.43	0.38	0.31	0.55	0.23	0.33
S. Africa	0.88	0.85	0.64	0.45	0.61	0.41	0.51	0.61	0.64	0.42	0.54
S. Korea	0.68	0.34	0.39	0.29	0.32	0.30	0.30	0.36	0.50	0.42	0.32
Sweden	1.07	1.14	0.82	0.88	1.78	1.23	1.26	1.14	1.35	1.14	1.24
Switzerland	1.18	1.04	1.15	1.54	1.84	1.19	1.51	1.66	1.07	0.51	1.37
Taiwan	0.55	0.62	0.50	0.33	0.65	0.33	0.40	0.32	0.44	0.33	0.35
Thailand	0.29	0.98	0.55	0.39	0.62	0.56	0.50	0.31	0.60	0.68	0.52
UK	1.13	1.26	1.02	1.05	1.44	1.13	1.37	1.09	1.39	1.11	1.14
US	1.59	1.25	1.51	1.36	2.57	1.20	1.30	1.48	1.26	1.16	1.42
Africa & M.East	0.71	0.84	0.65	0.82	0.63	0.65	0.44	0.87	0.66	0.56	0.61
C&S America	0.82	0.73	0.44	0.19	0.55	0.50	0.50	0.53	0.52	0.34	0.45
Rest of world	0.32	0.62	0.38	0.38	0.39	0.51	0.57	0.47	0.45	0.33	0.39
APEC	1.28	1.12	1.27	1.17	1.75	1.09	1.08	1.20	1.16	1.10	1.21
TOTAL	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00

a See note a from table C.2 and formula 6 in appendix B.

For example, the number of citations per paper in agriculture for Australia is 22 per cent greater than the number of citations per paper in agriculture for the world as a whole.

Source: ISI database.

Table C.5 Niches of comparative advantage and disadvantage in codified science, 1981-1994 [a]

	agric	*astron*	*biolog*	*chem*	*clinmed*	*comput*	*ecology*	*engin*	*geosci*	*immune*
Australia	■	■				✗	■		■	
Canada	■						■		■	✗
Chile	■	■				✗	■	✗		✗
Denmark			■		■	✗			✗	
Finland		✗	■	✗	■		■		✗	■
France				■	✗	✗	✗		■	
Germany		■		■	✗		✗		✗	✗
Hong Kong	✗	✗			■	■		■	✗	✗
India	■			■	✗			■		✗
Indonesia	■			✗		✗	■		■	
Italy		■		■			✗		✗	
Japan	■	✗		■			✗		✗	
Malaysia	■	✗		■		✗	■			
Mexico	■	■	✗			✗	■			✗
Netherlands		■					■	✗	✗	■
New Zealand	■	✗				✗	■		■	✗
Norway		✗			■		■		■	■
PNG	■	✗			■	✗				■
P.R. China			✗					■		✗
Philippines	■	✗		✗			■			■
Singapore		✗		■		■		■	✗	✗
S. Africa		■				✗	■		■	✗
S. Korea				■		■		■		✗
Sweden		✗			■	✗	■		✗	■
Switzerland	✗						✗			■
Taiwan		✗		■		■		■	✗	✗
Thailand	■	✗			■	✗				■
UK				✗	■	✗	✗			
US	✗			✗	■	■	■			
Africa & M.East	■	✗				■	■		✗	
C&S America	■	■			✗	✗	■			
Rest of world				■	✗		✗			✗
APEC				✗		■	■	■	■	

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Table C.5 continued

	mater	*maths*	*microb*	*molec*	*multi*	*neuro*	*pharm*	*physic*	*plant*	*psych*
Australia	×			×		×		×	■	
Canada	×			×	×			×	■	■
Chile		■		×					■	×
Denmark	×				×	■	■	■		×
Finland					×		■			×
France		■			■			■	×	×
Germany	■			■				■		×
Hong Kong		■						×		■
India	■			×	■	×				×
Indonesia		×			■	×		×	■	
Italy		■	×				■	■	×	×
Japan	■				×		■	■		×
Malaysia		■				×		×	■	×
Mexico		■		×					■	×
Netherlands	×		■		×				■	×
New Zealand	×						■	×	■	
Norway	×			×	×			×	■	
PNG	×				■		×	×	■	
P.R. China	■	■		×	■	×		■		×
Philippines	×	×			■			×	■	
Singapore	■	■			×					×
S. Africa				×	■	×			■	×
S. Korea	■			×	×	×		■		×
Sweden		×			×	■	■			
Switzerland		×		■	■		■	■	×	×
Taiwan	■	■		×						×
Thailand	×	×	■		■			×		
UK	×		■			■	■	×	■	
US				■			×	×	×	■
Africa & M.East		■				×	×		■	×
C&S America		■		×		×			■	×
Rest of world	■	■			■	×		■		×
APEC		×			×		×	×		■

a This table is based on the citation share data (CSH in table C.3). For each country, we have ranked the shares by field running from top to bottom. The top five fields (in terms of world share) for a given country are marked by a box, while the bottom five fields are marked by a cross. Thus for Australia, plant science ranks as first (with nearly 5 per cent of world citations) while physics ranks as last with less than 1 per cent of world citations.

Source: ISI database.

Table C.6 Absolute advantages and disadvantages: high and low citation shares by field by country [a]

	agric	*astron*	*biolog*	*chem*	*clinmed*	*comput*	*ecology*	*engin*	*geosci*	*immune*
Australia	■	■					■	■	■	
Canada	■	■	■	■	■	■	■	■	■	■
Chile										
Denmark										
Finland										
France	■	■	■	■	■	■		■	■	■
Germany	■	■	■	■	■	■	■	■	■	■
Hong Kong										
India	■									
Indonesia										
Italy		■		■	■	■		■		
Japan	■		■	■	■	■	■	■	■	■
Malaysia										
Mexico										
Netherlands		■	■				■			■
New Zealand										
Norway										
PNG				✗						
P.R. China										
Philippines										
Singapore										
S. Africa										
S. Korea										
Sweden			■		■		■			
Switzerland										■
Taiwan										
Thailand										
UK	■	■	■	■	■	■	■	■	■	■
US	■	■	■	■	■	■	■	■	■	■

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Table C.6 continued

	mater	maths	microb	molec	multi	neuro	pharm	physic	plant	psych
Australia	■	■	■						■	■
Canada	■	■	■	■	■	■	■		■	■
Chile										
Denmark										
Finland										
France	■	■	■	■	■	■	■	■	■	
Germany	■	■	■	■	■	■	■	■	■	■
Hong Kong										
India	■									
Indonesia		×								
Italy		■				■	■	■		
Japan	■	■	■	■	■	■	■	■	■	
Malaysia										
Mexico										
Netherlands			■	■					■	■
New Zealand										
Norway										
PNG	×	×					×	×		
P.R. China										
Philippines		×								
Singapore										
S. Africa										
S. Korea					×					
Sweden						■	■			■
Switzerland				■	■			■		
Taiwan										
Thailand										
UK	■	■	■	■	■	■	■	■	■	■
US	■	■	■	■	■	■	■	■	■	■

a Based on the top and bottom eight performers in terms of citation shares among 79 countries. The dark square denotes a country and a field which is represented in the top 10 per cent decile in terms of international citation share. The cross denotes the bottom 10 per cent decile. For example, Australia is in the top decile of countries in terms of citation shares in agriculture, while Papua New Guinea (PNG) is in the bottom decile in chemistry. We have not included all countries in the listing. We have included ones which are important in science or which are important for regional comparisons. This is why there are few countries with crosses.

Source: ISI database.

Table C.7 Absolute quality advantages and disadvantages: high and low citation rates by field by country [a]

	agric	*astron*	*biolog*	*chem*	*clinmed*	*comput*	*ecology*	*engin*	*geosci*	*immune*
Australia		■		■			■	■	■	
Canada	■			■	■	■				
Chile		■								
Denmark	■		■			■		■		
Finland										
France										
Germany			■							
Hong Kong										
India										
Indonesia										
Italy										
Japan										
Malaysia										
Mexico						■				
Netherlands	■	■		■		■	■			
New Zealand										
Norway							■			
PNG				x						
P.R. China										
Philippines				x						
Singapore										
S. Africa										
S. Korea										
Sweden	■	■	■	■	■		■	■		
Switzerland		■	■	■		■	■	■	■	■
Taiwan										
Thailand										
UK	■	■	■		■				■	■
US	■	■	■	■	■	■	■	■	■	■

Continued overleaf

Table C.7 continued

	mater	*maths*	*microb*	*molec*	*multi*	*neuro*	*pharm*	*physic*	*plant*	*psych*
Australia	■	■							■	■
Canada			■		■	■				■
Chile										
Denmark	■	■			■	■	■	■	■	■
Finland								■		
France										
Germany			■	■				■		
Hong Kong										
India									×	
Indonesia										
Italy										
Japan										
Malaysia										
Mexico										
Netherlands	■	■	■	■				■	■	
New Zealand							■			
Norway		■			■				■	
PNG										
P.R. China										
Philippines										
Singapore										
S. Africa										
S. Korea										
Sweden		■			■	■	■		■	■
Switzerland	■		■	■	■	■	■	■		
Taiwan										
Thailand										
UK	■	■	■	■		■	■		■	■
US	■	■	■	■	■	■	■	■	■	■

a Based on the top and bottom 10 per cent quartiles of citation rates. The dark square denotes a country and a field which is represented in the top decile (top eight countries) in terms of international citation rates per paper. The cross denotes the bottom decile. For example, Australia is in the top 10 percent of countries in terms of citation rates per paper in astronomy, while Japan lies in the middle 80 percent of countries for this field. We excluded countries which had less than fifty papers in a field from 1981 to 1994 inclusive from the calculations of rank.

Source: ISI database.

Table C.8 Relative growth rates in publication shares by field by country, 1981-1985 to 1990-1994 [a]

	agric	*astron*	*biolog*	*chem*	*clinmed*	*comput*	*ecology*	*engin*	*geosci*	*immune*
	(%)	(%)	(%)	(%)	(%)	(%)	(%)	(%)	(%)	(%)
Australia	0.65	-3.77	-0.49	-2.42	2.01	-0.82	1.45	0.97	0.92	0.54
Canada	4.10	0.78	0.65	-0.74	0.58	-0.15	-0.12	1.31	1.68	-0.47
Chile	4.29	3.33	-1.27	5.21	0.93	12.93	7.71	5.00	8.06	2.30
Denmark	2.99	5.22	-0.34	1.00	-1.92	3.16	3.32	0.69	-0.10	-3.04
Finland	3.34	7.44	0.41	0.61	-0.74	0.00	6.13	4.73	2.73	-2.86
France	1.77	1.71	1.19	0.96	-0.86	3.39	1.15	1.47	1.38	0.90
Germany	-2.13	-0.18	0.54	-0.39	-0.71	-2.31	0.27	-1.77	0.59	2.71
Hong Kong	9.95	23.27	2.78	6.35	9.80	8.01	7.85	8.89	-3.44	6.51
India	0.72	-0.61	-3.51	-2.64	4.37	-1.81	-3.39	-2.67	-0.12	5.90
Indonesia	3.40	11.40	5.36	7.80	-0.11	..	1.70	0.39	-2.16	-1.69
Italy	2.47	4.40	2.87	0.52	3.74	2.42	6.20	5.20	4.88	4.69
Japan	3.13	2.67	1.22	0.49	6.60	1.88	2.55	-0.12	2.42	2.70
Malaysia	2.24	-21.47	1.93	5.60	5.10	19.40	3.96	1.36	-1.57	-4.65
Mexico	7.17	5.33	6.39	4.28	-3.71	0.44	12.03	4.53	4.76	-0.08
Netherlands	4.23	-0.40	1.82	1.40	4.93	3.15	4.66	3.01	1.12	1.39
New Zealand	-1.52	-0.01	-2.75	0.11	0.84	2.10	1.58	-2.57	0.87	-2.39
Norway	-1.76	3.95	-0.35	-1.21	-1.35	-4.68	-0.56	2.48	4.33	-4.82
PNG	4.85	..	0.32	-3.31	-3.45	..	-6.55	-5.35	0.21	-0.90
P.R. China	20.83	5.86	13.41	14.29	4.82	10.09	14.13	13.67	-4.08	5.52
Philippines	2.27	..	-1.37	17.66	-8.93	3.76	1.36	0.11	9.60	14.18
Singapore	10.77	-16.11	9.98	17.16	4.90	15.87	8.78	15.10	4.41	30.63
S. Africa	3.40	-0.61	0.28	0.64	-5.04	1.24	2.36	0.82	3.30	2.20
S. Korea	12.54	18.15	17.68	16.83	20.73	26.92	17.36	18.71	13.37	15.11
Sweden	1.91	2.08	-0.71	0.93	-2.00	-4.57	3.19	3.91	3.05	-1.71
Switzerland	2.15	1.00	2.08	0.50	-0.22	-1.88	5.11	-2.23	4.96	-0.29
Taiwan	9.54	8.97	15.81	15.62	17.86	25.68	17.34	20.45	16.12	24.68
Thailand	9.90	..	4.48	1.02	-8.07	5.66	1.25	1.39	11.97	13.41
UK	-2.79	-1.22	-1.30	-1.10	0.67	-3.64	-0.75	-2.95	-0.03	-1.07
US	-2.13	-2.14	-0.87	-0.07	-1.02	-1.28	-2.37	-1.25	-1.21	-1.52

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Table C.8 continued

	mater	*maths*	*microb*	*molec*	*multi*	*neuro*	*pharm*	*physic*	*plant*	*psych*
Australia	-2.00	-2.96	1.14	-0.86	2.29	0.60	0.27	-0.49	-0.51	1.17
Canada	0.79	-0.16	-0.47	0.76	2.11	-0.19	-0.37	-0.49	0.17	1.50
Chile	-0.81	8.49	3.20	-4.25	-1.30	-0.55	2.25	2.83	2.86	2.36
Denmark	3.81	-0.73	3.31	-0.78	0.54	-3.62	2.09	-1.60	3.87	0.91
Finland	-2.83	-0.35	1.42	-1.66	-1.94	0.64	-1.00	0.63	4.85	10.58
France	2.80	1.78	2.60	0.70	-1.82	2.53	2.02	-0.33	1.30	5.68
Germany	-2.87	-1.33	0.24	-0.16	2.41	2.26	-2.21	-0.04	-0.89	1.19
Hong Kong	18.18	0.42	6.29	6.72	1.91	8.24	2.86	11.14	2.25	7.70
India	1.50	-5.31	-2.28	-5.18	-5.11	0.70	0.16	-2.39	-3.08	0.04
Indonesia	2.73	..	10.24	13.13	6.87	25.21	18.27	5.16	10.10	-4.10
Italy	4.77	5.11	1.07	3.72	0.17	4.33	1.62	1.84	4.95	5.85
Japan	3.62	-1.12	0.97	1.35	1.74	4.37	1.15	1.97	2.33	2.84
Malaysia	4.40	-10.37	6.79	-0.90	6.20	-5.47	16.85	6.80	1.38	4.80
Mexico	9.28	5.24	8.50	-0.98	9.39	1.32	4.85	4.35	8.36	8.72
Netherlands	4.90	-0.05	2.52	-0.63	5.83	2.41	1.60	0.48	2.68	6.33
New Zealand	-2.22	2.21	-3.26	1.12	-4.50	0.23	4.22	-2.00	0.48	1.85
Norway	-0.30	-2.38	-2.01	-1.44	-1.59	-2.56	-2.73	1.07	3.11	5.83
PNG	-17.56	2.15	10.66	-6.15	-3.54	..	..	..	-9.58	-12.89
P.R. China	20.60	12.92	12.28	8.13	7.89	13.47	11.79	15.47	-2.35	15.85
Philippines	0.10	..	-4.48	9.80	-19.96	-1.61	6.02	16.62	3.11	5.89
Singapore	17.52	7.44	12.80	11.75	-0.39	1.50	12.79	5.93	13.77	21.51
S. Africa	1.16	-1.23	1.34	1.25	6.48	-2.07	4.28	0.71	3.17	2.73
S. Korea	16.98	20.82	14.31	14.75	13.75	27.78	14.10	16.88	17.58	15.30
Sweden	-2.77	-0.56	-0.43	-0.42	5.68	-0.91	-2.18	1.58	4.99	0.19
Switzerland	-0.86	-1.00	1.47	0.07	0.00	-0.59	-0.81	-0.33	2.22	3.92
Taiwan	22.69	4.46	21.41	19.58	12.62	12.68	12.74	19.21	10.68	4.48
Thailand	-2.97	-21.85	5.99	-1.75	-3.48	6.79	5.61	-0.78	7.03	7.47
UK	-1.19	-2.64	-1.07	-0.56	0.26	-1.49	-0.15	-1.06	-2.43	0.73
US	0.43	-0.82	-0.99	-0.25	1.46	-1.47	-1.29	-0.93	-1.09	-1.33

a The data are based on the divergence between trends in country field shares and world field shares: $\Delta GRTREND_{ij} = trend(P_{ij} / \Sigma_{j=1} P_{ij}) - trend(\Sigma_{i=1} P_{ij} / \Sigma_{i=1} \Sigma_{j=1} P_{ij})$. The trend rates of growth in publication shares were estimated by regressing the logged value of publication shares against a time trend. Some values are zero, hence are not defined (..).

Source: ISI database.

Table C.9 Growth rates in relative citation impacts by field by country, 1981-1985 to 1990-1994 [a]

	agric	*astron*	*biolog*	*chem*	*clinmed*	*comput*	*ecology*	*engin*	*geosci*	*immune*
	(%)	(%)	(%)	(%)	(%)	(%)	(%)	(%)	(%)	(%)
Australia	-0.85	2.26	-0.09	-2.77	-0.54	-0.81	0.19	0.90	-0.10	-4.05
Canada	-2.23	3.44	-0.39	-0.97	0.52	-0.68	1.52	0.95	1.57	0.02
Chile	5.03	-2.56	0.47	-2.88	1.53	2.43	-8.67	-2.16	5.90	3.96
Denmark	-1.19	4.31	-0.40	-1.89	1.08	3.45	-0.71	-1.85	-2.55	0.96
Finland	0.55	1.24	2.04	-2.83	1.88	-0.01	-0.46	4.38	0.53	-3.15
France	3.26	1.45	0.65	-0.69	4.09	-1.73	4.15	3.16	0.93	0.16
Germany	1.00	1.06	0.21	-0.45	3.01	0.67	4.14	3.80	2.50	-0.04
Hong Kong	6.14	-6.53	-2.70	4.09	1.84	5.13	-1.60	5.70	-4.85	1.11
India	-5.94	3.41	-0.95	-0.09	0.48	0.37	1.39	-0.88	-4.25	-8.47
Indonesia	-1.43	5.59	1.88	-7.42	-5.32	..	7.31	3.01	3.11	-5.29
Italy	1.51	-0.14	1.10	0.18	3.76	3.93	1.66	3.93	-2.89	-0.99
Japan	-2.39	4.56	1.12	-0.11	0.54	-3.90	-1.50	-0.11	0.07	-0.47
Malaysia	-3.01	..	5.04	-1.67	2.50	..	-8.03	-4.28	7.79	0.54
Mexico	-4.24	-1.29	-6.72	-4.53	6.61	-15.86	1.76	2.78	-4.15	-2.56
Netherlands	1.32	-1.76	-0.24	-1.09	2.87	1.52	2.71	2.32	2.37	2.53
New Zealand	-0.66	-0.40	2.60	0.26	3.15	-0.17	-1.49	-2.79	1.91	0.71
Norway	0.58	3.00	-0.09	-3.34	-0.19	3.61	0.10	3.42	0.88	0.21
PNG	-3.38	..	5.73	-6.57	8.14	..	3.11	22.07	-5.58	-4.19
P.R. China	0.63	1.66	3.28	7.13	7.44	-6.89	-1.44	1.89	5.79	6.77
Philippines	-0.79	..	2.23	5.99	5.88	..	2.71	-1.70	-0.66	-16.27
Singapore	7.80	..	6.53	3.70	4.49	10.32	-3.78	3.23	-0.28	-0.68
S. Africa	-0.54	3.11	-0.67	0.19	0.97	0.51	-2.45	4.30	0.22	2.95
S. Korea	3.12	7.49	0.28	0.95	-1.51	-8.10	0.56	-2.41	4.18	-18.81
Sweden	-2.62	1.60	-2.01	-0.14	0.58	1.16	0.84	2.13	-0.08	-0.54
Switzerland	2.37	1.54	-0.60	-1.58	2.50	4.96	-0.47	4.35	-1.60	1.99
Taiwan	6.21	8.89	2.32	3.99	-6.42	-3.94	-11.50	-7.00	5.00	-10.97
Thailand	2.46	..	0.11	0.21	10.75	..	8.02	-1.36	8.57	-7.07
UK	-2.26	2.35	-0.37	-1.42	-1.23	1.93	-0.42	2.76	-1.74	1.03
US	1.29	-0.68	0.26	0.65	-0.82	0.57	0.03	-1.41	-0.25	0.71

Continued overleaf

Table C.9 continued

	mater	maths	microb	molec	multi	neuro	pharm	physic	plant	psych
Australia	-2.31	1.00	-1.40	-1.09	4.48	-1.02	-0.54	-0.07	-1.01	-0.03
Canada	-0.35	1.06	0.52	2.77	4.22	0.40	-1.53	2.35	-0.49	0.17
Chile	-1.16	3.58	12.25	-6.18	-1.40	-2.12	0.12	9.41	2.32	-1.43
Denmark	2.41	2.88	1.32	-4.53	0.41	-0.32	-0.25	-3.35	-1.61	-0.84
Finland	-1.52	0.61	-3.27	-0.20	5.85	2.88	1.38	-1.47	0.05	4.15
France	-2.75	-1.02	0.34	0.96	4.04	-1.07	0.02	-1.41	1.25	3.41
Germany	1.87	-0.59	-0.63	-0.11	4.12	2.54	-0.95	-0.37	0.51	2.21
Hong Kong	-1.57	6.33	8.49	3.32	-8.26	-6.66	1.91	-1.91	-4.35	2.06
India	-2.84	3.90	2.60	-1.10	3.16	-2.81	-2.43	2.19	-2.15	2.46
Indonesia	17.08	..	-9.28	-0.42	12.87	..	-1.05	-7.99	7.44	-8.55
Italy	-1.69	-0.86	2.86	-0.26	0.92	1.08	1.86	-0.90	0.52	1.49
Japan	-0.60	0.70	0.81	0.88	5.45	0.46	0.31	1.41	-0.71	4.26
Malaysia	-13.27	6.68	7.44	-7.68	3.81	-7.44	5.38	-9.24	0.97	-8.65
Mexico	-5.41	-6.79	0.20	-2.85	-5.32	0.38	-3.53	-4.14	-4.96	5.36
Netherlands	-5.75	0.37	1.65	-1.20	-0.44	-1.28	-2.25	0.64	1.41	-0.04
New Zealand	1.14	1.44	-2.12	-3.63	3.06	7.40	2.30	0.40	0.79	1.47
Norway	-1.03	-5.64	2.88	-3.77	4.18	-0.53	-2.32	-1.19	-0.44	0.15
PNG	..	..	-1.70	4.60	13.75	..	..	..	6.52	..
P.R. China	-3.01	-1.43	-3.12	7.20	-0.72	9.25	4.09	3.95	14.11	2.88
Philippines	..	..	8.51	8.87	24.57	16.70	0.54	..	-0.88	2.65
Singapore	0.70	-0.85	20.54	2.98	18.12	4.34	0.53	5.02	5.38	4.33
S. Africa	-1.93	3.82	0.82	-0.56	-0.97	0.87	-4.77	1.57	-1.52	-4.13
S. Korea	-4.42	6.43	-7.44	-2.76	19.58	-4.39	3.32	-2.92	-1.35	11.10
Sweden	-0.40	3.81	0.94	-2.68	9.43	-1.69	-0.04	-1.84	0.94	-1.21
Switzerland	4.99	0.56	-1.11	-3.38	5.38	-0.05	0.58	-2.24	3.31	2.32
Taiwan	1.21	-3.36	7.93	8.35	1.66	2.57	-3.35	0.98	6.56	3.88
Thailand	9.21	..	-1.97	-0.37	0.55	-11.83	3.95	0.38	-2.72	-9.11
UK	-2.25	1.43	-0.34	0.14	3.11	-0.25	4.01	-0.79	-0.31	-0.08
US	-0.81	-0.03	-0.07	0.34	-4.99	0.54	-0.17	0.49	0.10	0.24

a The data are based on the divergence between trends in country citation rates and world citation rates. The trend rates of growth in citation rates were estimated by regressing the logged value of citation rates against a time trend. Some values are zero, hence are not defined (..).

Source: ISI database.

Appendix D Could the decline be illusory?

As noted in the main text, citations accrue over time. In most fields, few papers are cited in the first or even second year. Over time, citations per paper slowly rise until they plateau – we call this path the 'time profile' of citations. However, this does not affect *relative* citation impacts, so long as all countries have the same and invariant shape of time profile. This appendix shows that if this is not true, then the data can give the false appearance of a decline in relative citation impacts. This does not mean we view this as a highly likely source of the change in Australia's relative citation impact – but we think it establishes a case for removing this factor as a potential explanator.

Say that there is no *long run* change in Australia's or the rest of the world's citation rates. That is, after many years an Australian paper published in 1981 or 1994 or any other year will get cited roughly the same amount. But imagine that the period taken to get to this long run grows over time for Australian papers. For example say that 15 years ago it took seven years for a paper to get cited on average 10 times. But now it takes seven and half years to be cited this amount. If this happens, the data from both the moving and fixed window data will suggest declining citation shares and relative citation impacts, even though by definition the long run relative citation rate remains fixed. We can illustrate how this could happen with a very simple model. We must distinguish first between the time that an article was published (denoted by t) and by its citation rate at time t+v. Say that citation rates at time t+v for papers written at time t for the ith country is given by the equation:

$$CITR_{itv} = e^{\left(\alpha_i - \frac{\beta_i}{v} + \frac{\phi_i}{v^2}\right)}$$

In this simple model α is the variable determining the long run citation rate while β and ϕ determine the path to the long run. Now it is possible that either α , ϕ or/and β change over time. People who claim that Australia is facing a crisis in science are implicitly suggesting that Australia's α is slowly falling over time. But there is another possibility. Say that $\beta_i = \Omega_i(t)$ and that this is *rising* over time. For a higher value of β the citation rate at any given time is lower, though in the long run it approaches the same value (e^{α_i}). Say in particular that for Australia: $\beta_t = \beta_{1981}(1.005^{t-1981})$ and that $\beta_{1981} = 5.9843, \phi = 2.011 \; and \; \alpha = 3.1028$. For the rest of the world suppose that $\beta = 5.639, \phi = 1.3366 \; and \; \alpha = 3.0802$. These values were estimated from the data on the profile of citation rates over time.[1] We use the estimated trend growth rates for papers to see how total papers change over time for t=1981 to 1994:

$$Papers_{Australia,t} = 10674 \times e^{0.0364\times(t-1981)} \; and \; Papers_{Rest\ of\ world,t} = 468{,}093 \times e^{0.0372\times(t-1981)}$$

1 In estimating the Australian parameters we imposed the constraint that the beta coefficient grew at 0.5 per cent per year. This is a very modest change. Such a modest change implies that after 14 years the citation rate for Australian papers is around 14.66 for the 1981 cohort of papers and 14.25 for the 1994 cohort. The fact that we can get such large changes in apparent relative citation

We can then estimate the citations for Australia, the rest of the world and the whole world as: $Citations_{i,t} = Papers_{i,t} \times CITR_{i,t,1994-t} \quad for\ t = 1981\ \ to\ 1994$, We can then calculate citation shares and relative citation impacts. An analogous set of calculations can be done to derive the fixed window results. The results (table D.1) suggest a steady decline in Australia's citation shares and relative citation impact even though we know that by *construction* the long run relative citation rate remains unchanged! We are not sure what citing practices could underlie such a change. But this remains as a theoretical possibility for the apparent decline.

Table D.1 How the declining rates could be spurious: some simulated numbers [a]

	Variable window			*Fixed window*	
	Citation share	*Relative citation impact*		*Citation share*	*Relative citation impact*
1981	0.022	1.012	1981-85	0.022	0.980
1982	0.022	1.007	1982-86	0.022	0.971
1983	0.022	1.001	1983-87	0.021	0.963
1984	0.022	0.994	1984-88	0.021	0.955
1985	0.022	0.987	1985-89	0.021	0.946
1986	0.022	0.978	1986-90	0.021	0.938
1987	0.021	0.969	1987-91	0.021	0.930
1988	0.021	0.957	1988-92	0.020	0.921
1989	0.021	0.943	1989-93	0.020	0.913
1990	0.021	0.925	1990-94	0.020	0.905
1991	0.020	0.902			
1992	0.019	0.872			
1993	0.019	0.840			
1994	0.021	0.943			

a The simulated numbers replicate the major features of the real data, showing declining citation shares and relative citation impacts even though by construction the long run relative citation rate is unchanged.

Source: Calculations using the algorithm described above.

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rates out of a modest change in the parameters of the process determining citation rates increases the plausibility of our results. The alpha coefficients suggest a long run citation rate of about 22 for either Australian or rest of world papers.

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