Technological Forecasting & Social Change 78 (2011) 1174–1182

Contents lists available at ScienceDirect

Technological Forecasting & Social Change

Bibliometry and nanotechnology: A meta-analysis

Yasuyuki Motoyama*, Matthew N. Eisler

Center for Nanotechnology in Society, University of California, Santa Barbara, Santa Barbara, CA 93106-2150, United States

ARTICLE INFO

Article history:
Received 30 October 2010
Received in revised form 6 March 2011
Accepted 13 March 2011
Available online 11 April 2011

Keywords:
Bibliometry
Citation
Country comparison
Impact factor
Metric
Nanotechnology

ABSTRACT

As in other fields of science, bibliometry has become the primary method of gaging progress in nanotechnology. In the United States in the late 1990s, a period when policy makers were preparing the groundwork for what would become the National Nanotechnology Initiative (NNI), bibliometry largely replaced expert interviews, then the standard method of assessing nanotechnology. However, such analyses of this sector have tended not to account for productivity. We hope to correct this oversight by integrating economic input and output measurements calculating academic publications divided by the number of researchers, and accounting for government investment in nanotechnology. When nanotechnology journal publication is measured in these ways, the U.S. is not the leader, as has been widely assumed. Rather, it lags behind Germany, the United Kingdom, and France.

© 2011 Elsevier Inc. All rights reserved.

1. Introduction

Bibliometric analyses of science, technology, and engineering have mushroomed in recent years. Researchers typically use this method to trace the quantity of output, usually defined as academic journal articles or patents, then compare and rank the state of science and engineering in different nations. Over the years, this has become a widely accepted benchmark.

But quantifying the practical value or economic productivity of knowledge produced through the systematic study of nature is extremely difficult. Developing the science of the assessment of science has been a protracted and troubled affair, as Benoît Godin notes. The question of science productivity began to be seriously considered following the emergence of professional disciplines of physical science around the mid-nineteenth century. Productivity was then defined by statisticians using simple quantitative metrics based initially on the total number of scientists in a given nation and subsequently on the total number of papers produced by individual scientists. The problem became much more complicated in the 1920s and 1930s, when governments became interested in developing means of measuring the contribution of knowledge to economic growth. Following the Second World War, the issue sharpened thanks to the popularization of the idea that basic science was the essential ingredient in radical technological innovation, and, hence, economic development, and the decision of the U.S. federal government to sponsor large-scale programs of basic science [1–3].

Government efforts to measure and account for these programs encouraged contractors to develop a linear innovative structure based on segregated organizational units of research, development, and manufacturing. Defining the productivity of non-mission, undirected basic research was especially contentious, provoking fierce debates and conflicting findings in the 1960s [4]. Over the years, however, the methodology of the science of the assessment of science productivity remained essentially unchanged. It continued to be based on quantity of outputs, typically academic journal articles or patents. In 1973, Congress mandated the National Science Board to publish *Science and Engineering Indicators*, which became an authoritative index of the state of science and engineering productivity in the U.S. [5]. By the 1990s and 2000s, bibliometric analysis of science, technology, and engineering activities was becoming the "customary" indicator of research output in a number of countries [6].

---

* Corresponding author. Tel.: +1 805 893 5929; fax: +1 805 893 7995.
E-mail addresses: ymotoy@cns.ucsb.edu (Y. Motoyama), meisler@isber.ucsb.edu (M.N. Eisler).

0040-1625/$ – see front matter © 2011 Elsevier Inc. All rights reserved.
doi:10.1016/j.techfore.2011.03.013

The question of productivity is especially pressing in the case of nanotechnology. Its proponents have framed this interdisciplinary field as a novel and especially fecund form of applied science, one some famously suggested might be capable of triggering a new industrial revolution [7]. Nanotechnology boosters emerged in the U.S. in the early 1990s, a period when science policy culture increasingly emphasized federal government-backed R&D as the primary means of closing the gap with America's economic competitors [8,9]. It is no coincidence that nanotechnology discourse in policy circles has been most prevalent in the U.S., where the belief in basic science as an economic driver has been strongest. Nevertheless, similar assumptions took root elsewhere, as R&D budgets swelled in a number of other countries over the last three decades. And although research in nanoscale science, engineering, and technology was performed abroad in the 1990s, these activities assumed greater prominence after the NNI was introduced in early 2000 [10,11]. As nanotechnology's prestige as a cutting-edge utilitarian frontier field grew in science policy communities and expectations for an economic dividend mounted, so, too, did bibliometry assume increased importance.

But the science of assessment itself has attracted as much scrutiny as the productivity claims of the basic science community [12]. Critics note that the emphasis on quantity of publications can foster a herd mentality, encouraging trends that sometimes yield poor science. Some critics trace the problem to the current incentive regime in the sciences, where output is not directly proportional to the effort invested, unlike some other fields. For example, this system does not value ‘failed’ but useful negative data [13]. Productivity claims for nanotechnology are even more problematic than for other areas of science and engineering both because of the high expectations associated with the field and the tendency of its proponents to subsume existing physical science disciplines under its rubric. As a number of scholars have noted, nanotechnology advocates presented old arguments for the economic utility of science in a new form [14–16].

Accordingly, it is imperative to carefully review the ways bibliometry has been used to assess nanotechnology. Perhaps surprisingly, previous bibliometric studies have tended not to account for productivity in nanotechnology publication. We hope to correct this oversight via two indicators: calculating the academic publications divided by the number of researchers and the resources invested in nanotechnology. We believe the resulting assessment of relative national efficiency provides a more accurate measure than the current metric of academic publication, which obscures the meaning of resource efficiency and tends to promote only quantitative increase.

2. The history of bibliometry and nanotechnology

As policy entrepreneurs laid the foundation of what would become the NNI in the late 1990s, they relied primarily on expert interviews to assess the state of U.S. competitiveness in nanotechnology. But this method was criticized by some scientists because there was no way to define objective expertise. There was also a conflict of interest because policy entrepreneurs interviewed experts who had an interest in a national nanotechnology initiative and the increased resources such a program would bring in this field and who actively took part in the lobbying process (see, for example, [7,17–20]). Accordingly, some scientists were uncomfortable with the conclusion of the Interagency Working Group on Nanoscience, Engineering, and Technology (IWGN) that the U.S. effort in nanotechnology was insufficient [21]. Perhaps aware of these concerns, U.S. nanotechnology policy advisors had largely replaced expert interviews with bibliometric analysis by the end of the first decade of the twenty-first century. The President's Council of Advisors on Science and Technology (PCAST) stated in its periodic review that:

> “In the course of this review, the NNAP (National Nanotechnology Advisory Panel) considered numerous efforts to collect and analyze such data on research output and commercialization efforts underway in the United States and around the world. While available data and viable metrics are limited, the panel found bibliometric analyses (numbers of publications and citations) and patent counts to be the most salient metrics for purposes of its assessment of the NNI's progress and the relative position of the United States with respect to the rest of the world” [22].

Although the PCAST acknowledged the limitations of bibliometry and the availability and challenges of other indicators in this 2008 report, it continued to employ it as a primary metric, using it in its most recent review [23]. By this standard, the U.S. dominated the field of nanotechnology. For example, Kostoff, Koytcheff, and Lau [24] found that the U.S. led total publications and high-impact papers in 168 out of 256 subfields such as quantum dots, proteins, and cellular components. Leydesdorff and Wagner [25] calculated that the U.S. share of global nanotechnology publication rose from 28.7% in 2002 to 30.2% in 2006. A few studies, however, showed this lead to be tenuous. Shelton and Holdridge [26] observed that China and some European countries were significantly narrowing the gap with the U.S. [27–31]. The journal *Nature Nanotechnology* concluded in 2008 that China was poised to overtake the U.S. in annual output if it had not done so already [32]. Similarly, Lenoir and Herron [33] predicted that China would surpass the U.S. in biopharmaceutical-related nanotechnology in or around 2012.

Popular for its presumed objectivity and precision, bibliometry has helped reinforce the current system of incentives in which numbers count, with serious consequences for policymaking. The declining share and absolute number of U.S. publications in the early 2000s (see Table 1) caused such concern that the National Science Foundation (NSF) undertook a special study to examine the causes of flattening U.S. science and engineering indicators [6]. Yet quantity of publication alone reveals little of what science is productive of. It is no surprise that the U.S. produces the largest absolute number of academic publications, including those dealing with nanotechnology, because it is the largest OECD nation.[1] But what does this tell us of the efficiency of science policy and its value to the broader economy?

---

[1] In 2010, the U.S had a population of 307 million, compared with France (64 million), Germany (82 million), Japan (127 million), India (1156 million), and China (1323 million) [34].

Table 1
The number and share of publication by country.[a]
Source: [11].

Country	1995		2000		2002		2004		2007	
US	193,337	34.2%	192,743	30.6%	190,496	29.8%	202,084	29.3%	209,695	27.7%
China	9061	1.6%	18,479	2.9%	23,269	3.6%	34,846	5.1%	56,806	7.5%
Japan	47,068	8.3%	57,101	9.1%	56,347	8.8%	56,535	8.2%	52,896	7.0%
UK	45,498	8.1%	48,216	7.6%	44,643	7.0%	45,490	6.6%	47,121	6.2%
Germany	37,645	6.7%	43,509	6.9%	42,436	6.6%	43,010	6.2%	44,408	5.9%
France	28,848	5.1%	31,427	5.0%	30,531	4.8%	29,891	4.3%	30,740	4.1%
Korea	3803	0.7%	9572	1.5%	11,735	1.8%	15,255	2.2%	18,467	2.4%
World	564,645	100.0%	630,452	100.0%	638,381	100.0%	688,644	100.0%	758,142	100.0%

[a] This figure accounts for all science and engineering fields defined by the NSB, not only nanotechnology.

In addition to absolute publication numbers, scholars often use citation and publication in highly regarded journals as proxies for quality. We briefly summarize their shortcomings. Critical studies have identified five key limitations of citation, the most popular measure of quality. First, Thomson Reuter's ISI Web of Knowledge, the most frequently used database, has been criticized for covering fewer than half of all journals worldwide. Not only is this database incomplete, it is biased toward the English language and the U.S. Several studies have found that science and technology activities in Germany, France, and Japan tended to be underrepresented [35–40]. Interviews by the authors suggest that Chinese scholars tend to evaluate their performance against peer-reviewed journals written in English, suggesting that underrepresentation may be less of a factor in this case.[2] Nevertheless, the question of variation by nation is an important one.

Second, social networks play an important role in citation. Scholars in close proximity tend to cite each other more frequently, reinforcing the geographic bias [42–44].

The third weakness is that the citation count is frequently correlated with the length of the paper and the number of authors [45,46].[3] Hence, longer papers with more authors get higher citation counts. To further complicate matters, different disciplines have different ways of organizing research teams, which, in turn, affects the number of authors. Although collaborative work is common in all scientific fields, the average number of authors can vary widely, ranging, for example, from 2.0 in mathematics to 5.3 in physics, and 5.6 in medical fields [11].

The validity of comparing citation rates across fields is, hence, questionable. Yet current cross-country analyses aggregate all disciplines and do not distinguish these differences. Standardizing metrics across fields is among the most pressing and difficult challenges facing bibliometricians [47].

A fourth limitation is the tendency of researchers to cite themselves [48,49]. The current ISI Web of Knowledge has no corrective mechanism for this. It is almost impossible to detect and exclude self-citation, first because multiple authorship exponentially complicates tracking and, second, because some journals have a tradition of citing only the initial of the first name and, in collective publications, the first few authors, abbreviating the rest as ‘et al.’

Finally, a paper can be cited simply because it has been criticized as incorrect [50]. Moreover, authors may cite what they believe to be the most important articles, often for brevity, but works they did not cite can be as or even more important and influential [51]. In fact, journals such as *Nature* that aim for concise articles explicitly instruct authors to limit the number of references. These five limitations demonstrate that citation is not necessarily indicative of academic or intellectual merit [52,53].

Publication in highly regarded journals shares similar drawbacks. Calculating the impact factor by citation of a journal published in the previous two years, methodology used by the ISI, is more meaningful for fast-paced disciplines and for citing recent research [38,54,55]. Kostoff et al. [56] used a similar method to select and rank journals specializing in nanotechnology.

In contrast, disciplines that have lower and slower citation densities are likely to have lower impact factors [52]. Garfield [47] found that molecular biology and biochemistry papers averaged 45 references and their average citation life was about seven years. In contrast, mathematics, botany, and taxonomy papers averaged about 15 references and citation life were between 20 and 30 years. Articles published within the same journal such as *Nature*, for example, can exhibit a significant variance of citation by disciplines: 50–200 for immunology, 50–150 for cancer, molecular, and cell biology, and fewer than 50 for physics, paleontology, and climatology [57].

The heterogeneity of citations and journal publications further complicates the ability of researchers to quantify science output in the case of nanotechnology, which embraces several academic disciplines. International comparisons in this context are even more problematic because countries tend to specialize in certain of nanotechnology's constituent fields [24,58]. Arbitrary publishing practices can muddy the waters still further. Under pressure to increase their impact factor, some journal editors ask submitting authors to cite earlier publications in their journals. Others do not. Nevertheless, in-house citation does not necessarily improve article quality.

The impact factor, the most widely recognized proxy for journal quality, brings its own complications. An average figure, it is heavily influenced by a small number of frequently cited papers. For example, 89% of citations in *Nature* came from 25% of the articles it published [57]. Researchers frequently misuse this metric as a measure of individual quality. Moreover, although papers

---

[2] We additionally note that publications by Scandinavian scholars in English are strongly representative of top research in Scandinavian countries [41]. We thank one of the reviewers for this reference.

[3] Stanek [46] did point out, however, that papers longer than 80 pages tended to receive fewer citations.

Table 2
Publication and adjusted publications.
Kostoff, Koytcheff, and Lau [24].

	Publication		Pub/researcher		U.S.-adjusted publication		Rank
	1998	2005	1998 [a]	2005	1998	2005	2005
France	2026	2822	0.0130	0.0139	15,090	19,341	4
Germany	3690	5726	0.0155	0.0210	18,005	29,201	3
Japan	4590	8010	0.0070	0.0114	8155	15,770	5
Korea	922	4132	0.0100	0.0230	11,556	31,893	2
United Kingdom	1887	4017	0.0120	0.0230	13,883	31,939	1
United States	6904	14,848	0.0060	0.0107	6904	14,848	6
China	1860	11,768	0.0038	0.0105	4444	14,600	7

[a] Note: U.S. researchers in 1997.

published in high impact journals may have a higher probability of being of higher quality than papers published in journals of lower impact, this is not necessarily a guarantee of high quality. As Woodside noted, “citation rates of articles affect a journal's impact factor but not vice versa” [59].

Even new metrics that attempt to correct for such flaws have weaknesses. Measuring an author's article productivity and citation-based impact simultaneously, Jorge Hirsch's popular h-index has been criticized for running a cumulative score that remains fixed even after a researcher has dropped out of the field, making it impossible to assess current productivity. And in some cases, metrics of individual productivity are irrelevant in fields featuring large collaborative research teams [60].

3. Thinking more broadly

Given the limitations of relying on publication numbers and citations, it is important to consider other indicators and dimensions in order to measure productivity in science. The focus of the current bibliometric literature, particularly in nanotechnology, is almost exclusively on output. However, there are at least two other indicators to measure an input for science: the number of scientists and engineers and research and development expenditure. The NSB's *Science and Engineering Indicators* does gage these two inputs in separate chapters, although there has been little effort to explicitly connect inputs and outputs.[4]

This section introduces two indicators as the denominator: the total number of researchers[5] and government investment in nanotechnology. The OECD's *Main Science and Technology Indicators* provides the total number of researchers. Although it would be ideal to know the total number of nanotechnology researchers, it is extremely difficult to disaggregate this figure from the overall number of scientists and engineers owing to definitional problems and the relative rarity of the term ‘nanotechnology’ as a marker of professional identity. Disparate disciplinary structures and research institutions in different countries further complicate the problem. However, we believe our approach is reasonable because there is a high correlation – 0.84–0.99 – between the number of nanotechnology articles and the number of total publications in science and engineering (see Appendix 1 for details). Thus, we assume that the proportion of normalization will be similar among countries.

In 2006, the U.S. had the largest number of science researchers – 1.4 million – followed by China with 1.2 million, and Japan with 700,000 (see Appendix 2). These figures correlate to some degree with the total population, but only modestly −0.67. Consequently, this indicator better captures productivity than the number normalized by inhabitants.

We take a further step to analyze productivity by using government investment in nanotechnology as another denominator. This analysis is in line with Leydesdorff and Wagner's examination of costs per publication [63]. Although their analysis focused on all science and engineering fields, our focus on nanotechnology provides an advantage in this productivity measure. We measure scientific journal articles in nanotechnology, research that tends to be concentrated at universities and national laboratories and funded largely by the state.[6] Thus, excluding the private sector's research investment in nanotechnology hardly affects the productivity measure.

International comparative data on nanotechnology investment is surprisingly incomplete. We created a database on nanotechnology initiatives and/or science policy from three sources: reports from the national governments of the U.S. and Japan and data on European countries, South Korea, and the People's Republic of China from the report by the European Commission's Community Research and Development Information Service (CORDIS) [64] and Lux Research [65,66].

The figures from the latter two sources tell a similar story, but we present both of them to provide a range in our estimates. We calculated the foreign exchange rate between the Euro and U.S. dollar by averaging the rate of each twelve-month period based on Data360.org, an open-source website. For the numerator, we employed a meta analysis in which we extracted data from past

---

[4] The benchmark closest to the productivity measure provided by the NSB report is academic articles per million inhabitants, but this data is listed only in the Appendices 1 and 2 query. There are three possible exceptions; Adams and Griliches [61] and Shelton [30] only examined the general scientific and academic field, not nanotechnology. We discuss the third and most notable exception [63] in the next section.

[5] Although the data concerning researchers at educational institutions can be an alternative indicator, it is incomplete owing to nanotechnology's current state as a form of basic research, particularly for the U.S. since 2000 and for the U.K. between 1999 and 2004. This data also assumes that most nanotechnology research is conducted at universities, an assumption that does not hold in a cross-country comparison. France (12.1%), Germany (14.8%), and China (17.2%) have a significant workforce in government-owned research institutes engaged in basic research. In the U.S., in contrast, this figure is only 3.6% [62].

[6] Note that our measure of government investment is different from Government Intramural Expenditure on R&D (GOVERD) by Leydesdorff and Wagner [63]. Our measure is closer to GOVERD plus Higher Education Expenditure on R&D (HERD).

Table 3
Publication share and adjusted share.
Kostoff, Koytcheff, and Lau [76].

	Publication share	Rank	Adjusted%	Rank
France	7.4	5	53.5	2
Germany	11.6	4	58.3	1
Japan	15.1	2	31.3	5
Korea	4.5	7	42.1	4
United Kingdom	5.9	6	45.1	3
United States	24.0	1	24.0	6
China	11.6	3	19.2	7

Table 4
All author and first author publications.
Youtie, Shapira, and Porter [31].

	Publication				Publication/researchers					
	1995		2005		1995		2005			
	All authors	1st author	All authors	1st author	All authors	1st author	All authors	Rank	1st author	Rank
Germany	1,077	894	4,910	3,458	0.0047	0.0039	0.0180	1	0.0127	1
Japan	1,146	1,031	6,191	5,342	0.0017	0.0015	0.0088	4	0.0076	4
United States	3,112	2,836	14,247	12,183	0.0030	0.0027	0.0103	2	0.0088	2
China	507	472	9859	9252	0.0010	0.0009	0.0088	3	0.0083	3

studies instead of constructing a new bibliometric database. This is advantageous because our intention is to demonstrate how the overall bibliometric picture changes when the productivity dimension is considered. Instead of estimating for precision by proposing another text mining method, we demonstrate a range of a new picture using this method.

We identified five bibliometric studies of academic journal publications at the country level[7] and present the results case by case. Assessing the total number of publications, all five studies concluded that the U.S. was the leader, followed by either Japan or China, depending on the time period and methods of extraction. However, when normalizing for the total number of researchers, the U.S. is not the leader in any study. Instead, Germany or the UK assumes the lead. The U.S. is next, followed by Japan and China.

Other bibliometric studies such as Huang et al. [71], Li et al. [72], Chen et al. [73], Pilkington et al. [74], and Dang et al. [75] focus on nanotechnology patent activities. We excluded these studies because the science and engineering informing the production of patents may differ from that cited in academic journal publications, although there may be some overlap.[8] Kostoff leads one of the most productive teams in this method, publishing at least two country analyses. Kostoff, Koytcheff, and Lau [24] reported that the U.S., Japan, and Germany occupied the top three positions respectively in 1998. By 2005, the order had shifted to the U.S., China, and Japan. However, our analysis of publications per researcher showed that Germany led in 1998, followed by the UK and France. The U.S., on the other hand, was among the least productive. In 2005, the UK and South Korea emerged as the top countries (Table 2).

4. Productivity per researcher

Since the indicator of publication per researcher is a small figure with four decimal units, we calculated the number of publications adjusted to the U.S. to place matters in a comparative perspective. This figure refers to the number of expected publications if the country had the same number of researchers as the U.S. did in a given year. For instance, in 2005, the UK, South Korea, and Germany would have had twice as many publications as the U.S. had they as many researchers (31,939, 31,893, and 29,201 papers respectively, as compared to 14,848).

Kostoff, Koytcheff, and Lau [76] similarly found that the U.S. had the largest publication share in 2002 at 24%, followed by Japan at 15.1% and China with 11.6%. However, if we adjust this ratio by the number of researchers, Germany, France, and the UK take the lead (Table 3).

Tracing the publication of all listed and first authors, Youtie, Shapira, and Porter [31] found the U.S. led in both indicators throughout 1995 and 2005. But when the productivity measure is used, German researchers are the most productive, with their U.S. counterparts in second place (Table 4).

---

[7] There are at least four other studies of country-level academic publications among peer-reviewed journals. Of these, Hullmann [67,68] and Guan and Ma [27] presented only graphic results, for which we were unable to obtain the precise numeric data. We tested these three studies based on our visual estimate of their graphics and obtained essentially the same results as we present in this section. The data in the *Nature* editorial [32] was based on Youtie, Shapira, and Porter [31], which we address in this article. Several other studies used the bibliometric method, but their focus was not the country analysis. See, for example, Youtie and Shapira [69] for spatial trajectory in the southern U.S. and Huang et al. [70] for interdisciplinarity.

[8] Future studies should consider how to measure the productivity dimension of patents.

Table 5
Share of world publication.
Leydesdorff and Wagner [25].

	World share		US-adjusted World share		
	2002	2006	2002	2006	Rank
France	7.1	6.8	51.1	45.9	2
Germany	9.2	8.7	46.5	44.4	3
Japan	13.9	10.8	28.9	21.7	6
Korea	3.2	4.5	30.3	32.1	4
United Kingdom	8.5	6.0	65.4	48.5	1
United States	28.7	30.2	28.7	30.2	5
China	10.3	15.4	17.1	17.9	7

Table 6
Share of world publication.
Zhou and Leydesdorff [77].

		US-adjusted	
	Share	Share	Rank
France	5.8	40.2	3
Germany	8.1	42.0	2
Japan	8.8	18.2	6
Korea	2.7	24.1	5
United Kingdom	8.3	65.9	1
United States	30.5	30.5	4
China	6.5	9.8	7

Table 7
Productivity per research money (calculated from Kostoff, Koytcheff, and Lau [24]).

	Cordis est.	Lux est.
France	10.1	27.4
Germany	15.7	13.9
Japan	9.3	9.1
Korea	19.2	20.2
United Kingdom	24.3	25.1
United States	15.0	13.5
China	113.7	47.3

Although Leydesdorff and Wagner [25] reported a significant lead by the U.S. in both 2002 and 2006, it is clear that the UK, France, and Germany (most to least productive) are considerably more productive than the U.S. (Table 5).

Lastly, Zhou and Leydesdorff [77] reported U.S. dominance of publication share in 2004. However, this figure changes drastically when the higher productivity per researcher of the UK, France, and Germany is considered (Table 6).

5. Productivity per research investment

In this section, we reassess the productivity estimates of Kostoff, Koytcheff, and Lau [8] and Youtie, Shapira, and Porter [15], who collected data on the number of publications rather than the share of world publication (Tables 7 and 8).

However, when we considered the number of publications per unit of research money (U.S. $1 million), an intuitively simpler indicator than a percentage of world publication share per unit of research money, a different picture emerged. It becomes evident that the U.S. does not enjoy uniquely high productivity. Applying the CORDIS and Lux estimates in our calculations, U.S. $1 million in the U.S. produces between 13.5 and 15.0 publications, outpacing Japan (9.1–9.3) and rivaling Germany (13.9–15.7), but trailing South Korea and the UK.[9] There is a substantial gap in the CORDIS and Lux figures concerning spending in France and China, reflecting a large fluctuation in our estimate. The U.S. may outpace France according to the CORDIS data, but not by the Lux data. In either estimate, China seems to lead all countries by this productivity measure.

---

[9] Both CORDIS and Lux estimate that U.S. state governments annually invest around $330 million in nanotechnology research, but we excluded this figure from the context of international comparison. If we include this state investment, the denominator would be larger and estimated aggregate productivity would be even lower.

Table 8
Productivity per research money (calculated from Youtie, Shapira, and Porter [15]).

	Cordis est.	Lux est.
Germany	13.49	11.89
Japan	7.17	6.06
United States	14.41	12.95
China	95.28	39.59

6. Conclusion

When productivity per researcher and investment is considered, then, the U.S. is not the leader in nanotechnology publication. It trailed its European counterparts in all studies, behind Japan and Korea in data based on Kostoff et al. [24,76] and Zhou and Leydesdorff [77], and behind Korea in Leydesdorff and Wagner [25]. When productivity per unit of research money is used as the benchmark, the U.S. still did not rival the UK, instead approximating German productivity. China outperformed all nations by this measure, a discrepancy that can be explained in terms of relative national purchasing power and cost of labor, which relate to the asymmetrical pace of industrial development and trade and monetary policies.

When productivity is defined thusly, there is not much that U.S. science and technology policymakers can by themselves do to bridge the gap because the remedial tools are in the hands of Congress, the Federal Reserve, and top officials in the executive branch. However, there are other ways to define science productivity. We found that countries with relatively coordinated science and technology policies like Japan and the UK consider bibliometrically-defined science output as only one of several indicators of the productivity of those policies, not a goal of them. Accordingly, they do not frame science productivity solely in terms of quantitative growth and consider quality as well.

Of course, this raises new difficulties. Although there is a general linkage between basic research and the commercial development of certain science-based technologies, it is difficult to correlate *national* efforts in basic science with *national* economic productivity. History demonstrates that many great ideas informing technological innovation and industrial products like penicillin, photovoltaic power, spintronics, or lithium manganese oxide energy storage, for example, were developed by individuals in countries that did not commercially exploit this knowledge, or were not the first to do so, or were not as successful in so doing as other countries, for a host of reasons. Exploring these reasons lays well outside the scope of our study. But our work highlights the need for comprehensive comparative research that relates national science and technology policy with national industrial policy and illuminates nanotechnology's relative place in these policies as a field developed and promoted primarily by state entities.

We feel bibliometric measurement and its bias towards volume of publication reinforce a competitive, potentially harmful dynamics among researchers in the field of nanotechnology and in the physical sciences generally. Preoccupation with output in academic and policy discourse has helped overshadow the relationship with input as this pertains to productivity. Ongoing investment in increased publication output tends to be uncritically welcomed, but the resulting ‘gold rush’ mentality may result in lower quality and unmet expectations.

Yet the bibliometric method does have a place. Useful in some circumstances, it should not be the only factor that informs policy. Like all other metrics, it can be used inappropriately, as Garfield, inventor of the Science Citation Index, cautioned more than a decade ago [36]. We do not argue that our productivity indictor should replace the quantitative publication measure. Instead, we hope our research can play a role in fostering debate about what indicators should be traced and how they should be integrated for evaluation.

Acknowledgments

We appreciate input from Mikael Johansson in an early brainstorming exercise, comments from John Mohr on an early draft, and suggestions by W. Patrick McCray. We also thank the two anonymous reviewers for their criticism. This research is based in part upon work supported by the National Science Foundation under Cooperative Agreement No. 0531184. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the National Science Foundation or the Center for Nanotechnology in Society.

Appendix 1. Correlations between nanotechnology articles and total publications in science and engineering

Author(s)	Publication year	Sample years	Correlation
Zhou & Leydesdorff	2006	2004	0.9983
Kostoff et al.	2007b	2002	0.8889
Kostoff et al.	2007a	2005	0.9012
Youtie	2008	2005	0.8469
Leyesdorff & Wagner	2009	2002	0.9685
		2006	0.9509

Note: Pearson correlation.

Appendix 2. Total researchers by country in 2006

	Total researchers	US = 100%
France	211,129	14.8%
Germany	279,452	19.6%
Japan	709,691	49.8%
Korea	199,990	14.0%
UK	176,213	12.4%
US	1,425,550	100.0%
China	1,223,756	85.8%

Source: OECD Main Science and Technology Indicators.

References

[1] B. Godin, On the origins of bibliometrics, Scientometrics 68 (1) (2006) 109–133.
[2] B. Godin, The value of science: changing conceptions of scientific productivity 1869-circa 1970, Soc. Sci. Inf. 48 (2009) 547–587.
[3] B. Godin, The Making of Science, Technology, and Innovation Policy, Centre-Urbanisation Culture Societe de I'Institut National de la Recherche Scientifique, Montreal, 2009.
[4] G.R. Asner, The linear model, the U.S. Department of Defense, and the golden age of industrial research, in: K. Grandin, N. Wormbs, S. Widmalm (Eds.), The Science-Industry Nexus, Science history Publications, Sagamore Beach, MA, 2004.
[5] H. Grupp, M.E. Mogee, Indicators for national science and technology policy: how robust are composite indicators? Res. Policy 33 (2004) 1373–1384.
[6] NSB, Science and Engineering Indicators, National Science Board, Washington DC, 2006.
[7] M.C. Roco, S. Williams, P. Alivisatos, Nanotechnology Research Directions: IWGN Workshop Report — Vision for Nanotechnology Research and Development in the Next Decade, WTEC, MD, 1999.
[8] D.S. Greenberg, Science, Money and Politics: Political Triumph and Ethical Erosion, University of Chicago Press, Chicago, 2001.
[9] J.N. Pierterse, Innovate, innovate! Here comes American rebirth, in: D. Araya, M.A. Peters (Eds.), Education in the Creative Economy, Peter Lang, New York, 2010.
[10] OECD, Science, Technology, and Industry Outlook, Organization for Economic Cooperation and Development, Paris, 2010.
[11] NSB, Science and Engineering Indicators, National Science Board, Washington DC, 2010.
[12] C. Macilwain, What science is really worth, Nature 465 (2010) 682–684.
[13] J. Rohn, How to improve the use of metrics, Nature 465 (2010) 870–872.
[14] A. Johnson, The end of pure science: science policy from Bayh–Dole to the NNI, in: D. Baird, A. Nordmann, J. Schummer (Eds.), Discovering the Nanoscale, IOS Press, Washington, DC, 2004.
[15] C. Mody, Introduction, Perspect. Sci. 17 (2) (2009) 111–122.
[16] J. Gallo, The discursive and operational foundations of the National Nanotechnology Initiative, Perspect. Sci. 17 (2) (2009) 174–211.
[17] WTEC, R&D Status and Trends in Nanoparticles, Nanostructured Materials, and Nanodevices in the United States, International Research Institute at Loyola College in Maryland, Baltimore, 1998.
[18] WTEC, Nanostructure Science and Technology: A Worldwide Study, WTEC, Loyola College, Baltimore, 1999.
[19] R.W. Siegel, E. Hu, M.C. Roco, R&D Status and Trends in Nanoparticles, Nanostructured Materials, and Nanodevides in the U.S. International Technology Research Institute, Baltimore, 1998.
[20] IWGN, Nanostructure Science and Technology: A Worldwide Study, Interagency Working Group on NanoScience, Engineering and Technology (IWGN), Washington DC, 1999.
[21] W.P. McCray, Will small be beautiful? Making policies for our nanotech future, Hist. Technol. 21 (2) (2005) 177–203.
[22] PCAST, The Second Assessment of the National Nanotechnology Initiative, President's Committee of Advisors on Science and Technology, Panel on Nanotechnology, Washington DC, 2008.
[23] PCAST, The Third Assessment of the National Nanotechnology Initiative, President's Committee of Advisors on Science and Technology, Panel on Nanotechnology, Washington DC, 2010.
[24] R.N. Kostoff, R.G. Koytcheff, C.G.Y. Lau, Technical structure of the global nanoscience and nanotechnology literature, J. Nanopart. Res. 9 (2007) 701–724.
[25] L. Leydesdorff, C.S. Wagner, Is the United States losing ground in science? A global perspective on the world science system, Scientometrics 78 (1) (2009) 23–36.
[26] R.D. Shelton, G. Holdridge, The US–EU race for leadership of science and technology: qualitative and quantitative indicators, Scientometrics 60 (3) (2004) 353–363.
[27] J. Guan, N. Ma, China's emerging presence in nanoscience and nanotechnology: a comparative bibliometric study of several nanoscience 'giants', Res. Policy 36 (2007) 880–886.
[28] B. Jin, R. Rousseau, Evaluation of research performance and scientometric indicators in China, in: H.F. Moed, W. Glanzel, U. Schmoch (Eds.), Handbook of Quantitative Science and Technology Research, Kluwer Academic, Dordrecht, 2004.
[29] L. Leydesdorff, The delineation of nanoscience and nanotechnology in terms of journals and patents: a most recent update, Scientometrics 76 (1) (2008) 159–167.
[30] R.D. Shelton, Relations between national research investment and publication output: application to an American paradox, Scientometrics 74 (2) (2006) 191–205.
[31] J. Youtie, P. Shapira, A.L. Porter, Nanotechnology publications and citations by leading countries and blocs, J. Nanopart. Res. 10 (2008) 981–986.
[32] Editorial, location, location, location, Nat. Nanotechnol. 3 (6) (2008) 309.
[33] T. Lenoir, P. Herron, Tracking the current rise of Chinese pharmaceutical bionanotechnology, J. Biomed. Discovery Collab. 4 (2009) 8.
[34] U.S. Census, International Population Clock: Country RankingsRetrieved May 12, 2010, from, http://sasweb.ssd.census.gov/idb/ranks.html,2010.
[35] E. Archambalut, E. Vignola-Gagne, G. Cote, V. Lariviere, Y. Gingras, Welcome to the linguistic warp zone: benchmarking scientific output in the social sciences and humanities, Paper presented at the Proceedings to the ISSI 2005, Stockholm, July 24–28 2005.
[36] E. Garfield, How can impact factors be improved? Br. Med. J. 313 (1996) 411–413.
[37] H. Grupp, M.E. Mogee, Indicators for national science and technology policy: their development, use, and possible misuse, in: H.F. Moed, W. Glanzel, U. Schmoch (Eds.), Handbook of Quantitative Science and Technology Research: The Use of Publication and Patent Statistics in Studies of S&T Systems, Kluwer Academic, Dordrecht, Netherlands, 2004.
[38] P.O. Seglen, Why the impact factor of journals should not be used for evaluating research, Br. Med. J. 314 (1997) 498–502.
[39] A.F.J. Van Raan, Measuring Science: Capita selecta of current main issus, in: H.F. Moed, W. Glanzel, U. Schmoch (Eds.), Handbook of Quantitative Science and Technology Research: the Use of Publication and Patent Statistics in Studies of S&T Systems, Kluwer Academic, Dordrecht, Netherlands, 2004.
[40] G.H. Whitehouse, Citation rates and impact factors: should they matter? Br. J. Radiol. 74 (2001) 1–3.
[41] G. Sivertsen, Bibliografiske detakilder til dokumentasjon av vitenskapelige publikasjoner, NIFU skriftserie nr, Oslo, Norway, 2003.

[42] J.S. Katz, Geographical proximity and scientific collaboration, Scientometrics 31 (1) (1994) 31–43.
[43] L.G. Zucker, M.R. Darby, M.B. Brewer, Intellectual Capital and the Birth of U.S. Biotechnology Enterprises, National Bureau of Economic Research, Cambridge, MA, 1994.
[44] L.G. Zucker, M.R. Darby, J. Furner, R.C. Liu, H. Ma, Minerva unbound: knowledge stocks, knowledge flows and new knowledge production, Res. Policy 36 (2007) 850–863.
[45] R. Leimu, J. Koricheva, What determines the citation frequency of ecological papers? Trends Ecol. Evol. 20 (1) (2005) 28–32.
[46] K.Z. Stanek, How Long Should an Astronomical Paper Be to Increase Its Impact? Ohio State University, Columbus, OH, 2008.
[47] E. Garfield, Dispelling a few common myths about journal citation impacts, Scientist 11 (3) (1997) 11–12.
[48] H.D. White, Authors as citers over time, J. Am. Soc. Inf. Sci. Technol. 52 (2) (2001) 87–108.
[49] S.D. Sala, J. Brooks, Multi-authors' self-citation: a further impact factor bias? Cortex 44 (2008) 1139–1145.
[50] P. Todd, R.J. Ladle, Hidden dangers of a ‘citation culture’, Ethics Sci. Environ. Polit. 8 (2008) 13–16.
[51] M.H. MacRoberts, B.R. MacRoberts, Problems of citation analysis: a study of uncited and seldom-cited influences, J. Am. Soc. Inf. Sci. Technol. 61 (1) (2010) 1–13.
[52] L. Bornmann, R. Mutz, C. Neuhaus, H.-D. Daniel, Citation counts for research evaluation: standards of good practice for analyzing bibliometric data and presenting and interpreting results, Ethics Sci. Environ. Polit. 8 (2008) 1–10.
[53] P.A. Todd, Ambiguity, bias, and compromise: an ABC of bibliometric-based performance indicators, Environ. Plann. A 41 (2009) 765–771.
[54] H.W.C. Yeung, Deciphering citations, Environ. Plann. A 34 (2002) 2093–2106.
[55] S.D. Sala, J.R. Crawford, Impact factor as we know it handicaps neuropsychology and neuropsychologists, Cortex 42 (2006) 1–2.
[56] R.N. Kostoff, J. Murday, C.G.Y. Lau, W. Tolles, The seminal literature of nanotechnology research, J. Nanopart. Res. 8 (2006) 193–213.
[57] Editorial, not-so-deep impact, Nature 435 (7045) (2005) 1003–1004.
[58] R.N. Kostoff, J.A. Stump, D. Johnson, J. Murday, C.G.Y. Lau, W. Tolles, The structure and infrastructure of the global nanotechnology literature, J. Nanopart. Res. 8 (2006) 310–321.
[59] A.G. Woodside, Journal and author impact metrics: an editorial, J. Bus. Res. 62 (2009) 1–4.
[60] R.V. Noorden, A profusion of measures, Nature 465 (2010) 864–866.
[61] J. Adams, Z. Griliches, Measuring science: an exploration, Proc. Natl Acad. Sci. 93 (1996) 12664–12670.
[62] OECD (Organization for Economic Cooperation and Development), Main Science and Technology Indicators, 2010.
[63] L. Leydesdorff, C.S. Wagner, Macro-level indicators of the relations between research funding and research output, J. Informetrics (3) (2009) 353–362.
[64] EC (European Commission), Some figures about Nanotechnology R&D in Europe and Beyond, Brussels, European Commision, Research DG, Unit G4 Nanosciences and Nanotechnologies, 2005.
[65] Lux, The Nanotech Report, 4th editionLux Research, New York, 2006.
[66] Lux, The Nanotech Report, 5th editionLux Research, New York, 2007.
[67] A. Hullmann, Who is winning the global nanorace? Nat. Nanotechnol. 1 (2006) 81–83.
[68] A. Hullmann, Measuring and assessing the development of nanotechnology, Scientometrics 70 (3) (2007) 739–758.
[69] J. Youtie, P. Shapira, Mapping the nanotechnology enterprise: a multi-indicator analysis of emerging nanodistricts in the US South, J. Technol. Transf. 33 (2008) 209–223.
[70] C. Huang, A. Notten, N. Rasters, Nanoscience and technology publications and patents: a review of social science studies and search strategies, J. Technol. Transf. 36 (2) (2010) 147–172.
[71] Z. Huang, H. Chen, A. Yip, G. Ng, F. Guo, Z.-K. Chen, et al., Longitudinal patent analysis for nanosccale science and engineering: country, institution and technology field, J. Nanopart. Res. 5 (2003) 333–363.
[72] X. Li, Y. Lin, H. Chen, M.C. Roco, Worldwide nanotechnology development: a comparative study of USPTO, EPO, and JPO patents (1976–2004), J. Nanopart. Res. 9 (2007) 977–1002.
[73] H. Chen, M.C. Roco, X. Li, Y. Lin, Trends in nanotechnology patents, Nat. Nanotechnol. 3 (2008) 123–125.
[74] A. Pilkington, L.L. Lee, C.K. Chan, S. Ramakrishna, Defining key inventors: a comparison of fuel cell and nanotechnology industries, Technol. Forecast. Soc. Change 76 (2009) 118–127.
[75] Y. Dang, Y. Zhang, L. Fan, H. Chen, M.C. Roco, Trends in worldwide nanotechnology patent applications: 1991 to 2008, J. Nanopart. Res. 12 (2010) 687–706.
[76] R.N. Kostoff, R.G. Koytcheff, C.G.Y. Lau, Global nanotechnology research literature overview, Technol. Forecast. Soc. Change 74 (2007) 1733–1747.
[77] P. Zhou, L. Leydesdorff, The emergence of China as a leading nation in science, Res. Policy 35 (2006) 83–104.