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Bibliometry and nanotechnology: A meta-analysis

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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.

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].

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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].