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The emergence of social science research on nanotechnology

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Abstract This article examines the development of social science literature focused on the emerging area of nanotechnology. It is guided by the exploratory proposition that early social science work on emerging technologies will draw on science and engineering literature on the technology in question to frame its investigative activities, but as the technologies and societal investments in them progress, social scientists will increasingly develop and draw on their own body of literature. To address this proposition the authors create a database of nanotechnology-social science literature by merging articles from the Web of Science's Social Science Citation Index and Arts and Humanities Citation Index with articles from Scopus. The resulting database comprises 308 records. The findings suggest that there are multiple dimensions of cited literature and that social science citations of other social scientists' works have increased since 2005.

Keywords Nanotechnology · Societal implications · Scientometrics

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Introduction

Nanotechnology is defined as science, engineering, and technology related to "the understanding, control, and use of matter at dimensions of roughly 1–100 nm where unique characteristics enable novel applications" (President's council of advisors on science and technology, 2008, p. 5). Scientists from multiple fields are engaged in research at this nanoscale, including from biology, chemistry, electrical engineering and electronics, materials science, medicine and physics (Porter and Youtie 2009a, b). Numerous nanotechnology-enabled products are already on the market in cosmetics, environmental control systems, household and consumer appliances, sensors, sports equipment, textiles and other segments. More radical innovations, building on fundamentally new materials or devices assembled at the nanoscale, are foreseen for the future (Schmidt 2006). Nanotechnology is expected to have far-reaching influences as the driver of a new wave of technology-based business growth (Uldrich 2003; Joint Economic Committee 2007) and some argue that nanotechnology has already shifted from discovery to the commercialization phase (Lux Research 2007). Early evidence suggests that nanotechnology is becoming a general purpose technology that will have pervasive effects across the economy (as discussed by Youtie et al. 2008a).

Substantial investments in nanotechnology R&D have been made in the US and other countries. Nearly $10 billion has been invested in multiple departments and agencies as part of the National Nanotechnology Initiative (NNI), including estimated spending of $1.5 billion in fiscal year 2009 (Shapira and Youtie 2010). Equivalent levels of investment are being made in Europe and Asia. Although most of these investments are focused in science and engineering areas, nanotechnology has raised particular interest in the societal implications of the technology. In the United States, the 21st Century Nanotechnology Research and Development Act (P.L. 108–153) was signed into law in 2003 with an explicit mission to integrate societal concerns into nanotechnology R&D and encourage citizen input. Section "Approach" (b)(10) of this act establishes a societal implications research program, requires nanoscale science and engineering research centers (NSECs) to address societal implications, integrates societal concerns with nanotechnology R&D, seeks nanotechnology advances that offer quality of life improvements for all, and provides for public input. The fiscal year 2009 budget for the NNI allocated 2.7% to societal and educational concerns. In addition, there are investments in research into the societal dimensions of nanotechnology in other countries, including projects on social, legal, and ethical implications supported under the European Union's Framework Programmes and other research programs (Hullmann 2008).

The US approach to incorporating societal perspectives into nanotechnology R&D investments emphasizes a close relationship between science and social science in the Nanoscale Science and Engineering Centers (NSEC). The US National Science Foundation (NSF) has created two NSECs devoted to the examination of societal issues: the Center for Nanotechnology in Society at Arizona State University (CNS-ASU) and the Center for Nanotechnology in Society at the University of California at Santa Barbara. In addition, there are Nanoscale Interdisciplinary Research Teams supported at the University of South Carolina, Michigan State University, and Harvard/University of California at Los Angeles/National Bureau of Economic Research, the latter of which is charged to create a NanoBank to examine nanotechnology's connection to society. NSF also encourages and supports social science involvement in the National Nanotechnology Infrastructure Network (NNIN), comprised of user facilities open to university and private sector scientists and engineers.

The engagement of researchers from social sciences and the humanities (including ethics) in the assessment of emerging technologies is not new to nanotechnology. For example, advances in medicine and, in recent years, biotechnology, have often been subject to broader societal review and deliberation. A case in point is the Human Genome Project (HGP), which (since its beginning in the late 1980s) was subject to significant assessment of its ethical, legal, and social implications (ELSI). About 3–5% of the HGP budget provided by the National Institutes of Health and the US Department of Energy was dedicated to programs of ELSI activities (Fisher 2005). Reviews of these ELSI activities have not acknowledged high levels of impact on influencing trajectories of scientific research or on policymaking (Marshall 1996; Fisher 2005). Still there continue to be appeals for, and interest in, increased social science involvement in the assessment of new technologies. Since the early 2000s, nanotechnology has been one the emerging domains where societal assessments have been embedded, as noted earlier, with programs funded in the US and other developed economies. Importantly, in this round, the scope of societal assessment has been broadened, incorporating not only ethical, regulatory and legal concerns associated with nanotechnology, but also calls to embrace issues of economic impact, equity, privacy and security, environmental effects, public deliberation, public perception, and the role of media and culture (Mnyusiwalla et al. 2003; Sheetz et al. 2005; Bennett and Sarewitz 2006).

This breadth of interest in its societal implications is surely related to nanotechnology's potential as a far-reaching and revolutionary platform or generic technology. Nanotechnology certainly encompasses a wide range of scientific and engineering disciplines (see Siegel et al. 1999). However, there is much interest (and debate) from both science and policy perspectives as to the extent to which these science and engineering disciplines may be interrelating, if not converging, at the nanoscale. On one side, Roco & Bainbridge (2002a) coin the term "nano-bio-info-cogno" (NBIC) to advance their view that the disciplines engaged in nanotechnology are increasingly likely to coalesce together as the field develops. On the other side, Schummer (2004) and Meyer (2006) find that there is little integration and collaboration among disciplines within the framework of nanotechnology. Porter and Youtie (2009a, b) offer a variant: they observe that nanotechnology is multidisciplinary, albeit not substantially more so than other recent emerging fields that make use of knowledge in multiple areas of science and technology.

These ongoing debates about disciplinary convergence and the exchange of knowledge across disciplinary boundaries in nanotechnology have analogues on the social science side. While we do not expect the diverse branches of academia engaged in the study of the societal implications of nanotechnology to converge their research activities into an amalgamated discipline, it is likely that there will be new interdisciplinary collaborations and exchanges of knowledge across traditional disciplinary boundaries among social scientists and between social scientists and nanotechnology natural scientists and engineers. Indeed, research sponsors and academy studies have encouraged and supported interdisciplinary collaboration in investigating nanotechnology's societal impacts (Roco and Tomellini 2002; Roco 2003; Royal Society 2004, p. 56). Professional associations and scholarly conferences have also been initiated to advance intellectual exchange among social scientists engaged in study of the implications of nanotechnology in society.[1] It is thus appropriate and relevant to probe interdisciplinarity and the exchange of knowledge

[1] See, for example, the Society for the Study of Nanoscience and Emerging Technologies, http://www.thesnet.net. Accessed December 20, 2009, and an earlier organization, the International Nanotechnology and Society Network. http://www.nanoandsociety.com. Accessed December 20, 2009.

across respective disciplinary boundaries among those engaged in the study of the societal impacts of nanotechnology. We anticipate that there will be an evolution in the characteristics and sources of interdisciplinary knowledge sharing which reflect the development of nanotechnology as a domain of scientific enterprise and growth in the availability, scale, and sophistication of societal analyses. We hypothesize that early social science work on emerging nanotechnologies will draw on science and engineering literature—and even science fiction—to frame its investigative activities. But as these technologies progress, social scientists will begin to develop their own body of literature, including foundational and theoretical concepts as well as accumulated work specific to the emerging technology. The results will show that there are increasing numbers of social science publications addressing nanotechnology. A change in citation patterns accompanying this growing body of social science literature on nanotechnology is observed which suggests that social scientists are increasingly developing a body of self-influential societal research alongside that which exists in science and engineering.

Approach

As part of the Center for Nanotechnology and Society at Arizona State (CNS-ASU), we—along with other colleagues at Georgia Institute of Technology—have been compiling and analyzing research papers and patents relating to nanotechnology science and engineering (Porter et al. 2008a, b).[2] In this article, a companion effort to retrieve social sciences and humanities literature pertaining to nanotechnology is described. In September–October of 2007, we conducted searches of the Social Science Citation Index and Arts and Humanities Citation Index (SSCI/AHCI) of the Web of Science (WOS) for nanotechnology-related publication records.[3] The initial search term was "nano*". In addition, further search terms taken from the approach detailed in Porter et al. (2008a, b) were applied, including combinations of quantum dot, quantum well/wire/self-assembly, and molecular motor/engineering/electronics/device. The term "nano*" returned the majority of publications, although nine additional publications were uncovered through the additional search terms. The raw number of articles retrieved from this basic WOS search was 540. These records were then checked against the exclusion terms that the authors had used in developing nanoscience and engineering datasets (Porter et al. 2008a, b). As a result we removed some articles that referenced only sodium nitrite (NaNO2) or sodium nitrate (NaNO3), biblical references with nano embedded in the title or abstract terms ("Nano Bible"), articles related to nanotechnology applications for conservation in archeology and art, references to "Nanook of the North" (a 1922 documentary film about an Inuit family in Canada), duplicate records, and other non-germane articles. That gave us more than 330 possible publication records in the social sciences related to nanotechnology. To put this size into perspective, there were more than 400,000 nanoscience and engineering publications uncovered in the search of the WOS Science Citation Index (SCI) described in Porter et al. (2008a, b). After reviewing this database of nanotechnology-related social science publications, it was determined that a focus on journal articles would be important and appropriate. Two-thirds of the SSCI/AHCI publications were articles, with the remaining

[2] See http://www.nanopolicy.gatech.edu

[3] The Web of Science (Thomson Reuters) indexes over 10,000 journals worldwide, including more than 2,400 in social sciences and nearly 1,400 in arts and humanities. See: http://thomsonreuters.com/products_services/science/science_products/a-z/web_of_science. Accessed December 20, 2009.

publications being mostly editorials, book reviews, and news and meeting announcements. A focus on articles allows us to examine full-length, peer-reviewed, and substantively rich contributions to the literature on nanotechnology from the social sciences. Analysis of the cited references within these articles also allows identification of connections with other literatures of social science, including books and non-scholarly works (Hicks 2005).

The WOS-based article database was supplemented with publication records from Elsevier's Scopus database.[4] The Scopus search involved an initial test run using nano* + social sciences as the key search term. The test run produced 6,206 records, of which more than 80% were articles. However, a scan of the top journals and subject categories suggested the need for a second stage filtering, which limited publications to those focused on four subject categories: business, management and accounting (393); arts and humanities (292); social sciences (130); and economics, econometrics and finance (39). A third stage applying exclusion terms including out-of-scope journals and non-article publications produced 215 articles including business, management and accounting (109); arts and humanities (108); social sciences (33); and economics, econometrics and finance (28). These were then individually checked for duplications and relevance to nanotechnology and the social sciences.

Upon comparing the two datasets, we found that obtaining records from each of them was valuable because each source contributed some unique journals not found in the other. Scopus contributed articles not available from SSCI/AHCI in journals such as *Development, Foresight, Technology in Society*, *NanoEthics, Journal of Business Ethics*, and *Science and Public Policy*. SSCI/AHCI contributed articles not available from Scopus in journals such as *The Scientist, Scientometrics, Futurist, Technological Forecasting and Social Change, Health Risk & Society*, *Journal of Law Medicine and Ethics, Research-Technology Management, Interdisciplinary Science Reviews, and Issues in Science and Technology*. There also was some overlap, with 47 articles present in both sources, in journals such as *Research Policy, Futures, Science Communication, Technovation, Public Understanding of Science, and Area*.

We then merged the two databases, which after removing duplicate records, gave us a total of 308 articles. The analyses that follow are based on this merged dataset of nanotechnology-related social science articles.

Profile of nanotechnology-related social science articles

Of the 308 nanotechnology-related social science articles, nearly two-thirds were published in the 2005–2007 timeframe and more than one quarter were published in the 1998–2004 timeframe. There were 12 times more articles in the 2005–2007 period than the pre-1998 period and more than 2.6 more articles in the 2005–2007 period than the 1998–2004 period. Table 1 shows that almost half of all nanotechnology-related social science articles identified through WOS and Scopus have an author from a US institution. This is a higher share than the 24% accounted for in nanoscience and engineering (Youtie et al. 2008a, b). Authors at institutions in the UK account for 15% of these articles, followed by Germany (9%) the Netherlands (6%), and Belgium, Finland, and France (4% each). China which has dramatically increased its nanoscience and engineering publications, accounting for 20

[4] Scopus (Elsevier B.V) indexes over 16,500 peer-reviewed journals including more than 6,400 titles in social sciences and about 2,300 in arts and humanities, see: http://info.scopus.com. Accessed December 20, 2009.

Table 1 Nanotechnology-related social science articles: top countries of author affiliations

Affiliations (country)	Instances	Percent
United States	116	45.7
United Kingdom	38	15.0
Germany	22	8.7
Netherlands	16	6.3
Belgium	11	4.3
Finland	11	4.3
France	11	4.3
Australia	8	3.1
China	6	2.4
Spain	5	2.0
Switzerland	5	2.0

Source: Author analysis of 254 articles providing organizational affiliations (of 308 articles) excerpted from WOS SSCI/AHCI and Scopus. Retrieved September–October, 2007. 227 articles have authors with a single country affiliation; 16 and 11 articles have authors with two or three country affiliations respectively. Articles with co-authors from multiple countries are counted as multiple country instances. Total number of country instances is 292

percent of all nanoscience and engineering publications by 2006 (Youtie et al. 2008a, b), contributes less than 2% of social science nanotechnology publications in this dataset.

The most frequent keywords (besides nanotechnology) referenced in ten or more of the articles are: science, technology, nanoscience, ethics, patterns, innovation, biotechnology, future, collaboration, emergent technology, indicator, and interdisciplinary. The most frequent journal subject categories[5] (available only for the SSCI/AHCI records) are: Information Science & Library Science Computer Science, Interdisciplinary Applications Multidisciplinary Sciences Planning & Development Ethics Business Social Issues History & Philosophy Of Science Management Medical Ethics Social Sciences, Biomedical Law Social Sciences, Interdisciplinary Chemistry, Multidisciplinary Engineering, Multidisciplinary Medicine, and Legal (See Table 2).

Citations

We are able to identify two types of citations associated with the nanotechnology-related social science articles in our database. Forward citations—the first type—are references to particular articles contained in our database by other WOS articles. This citation information is available for about 80% of our database articles. We acknowledge that forward citation counts have been interpreted to measure a variety of diverse attributes, including utility, quality, and importance, and are influenced by differential citation practices across disciplines and institutions as well as by journal placement and elapsed time since publication (Moed 2005). Thirty-six of the nanotechnology-related social science articles for which citation information is available received five or more cites at the time of creation of the dataset. The distribution of cites received is the typical highly skewed pattern: 106

[5] Subject Categories are part of the Journal Citation Reports of the Institute for Scientific Information (ISI) of Thomson Scientific's Web of Knowledge. These subject categories derive from a combination of inter-journal citation data and expert editorial perspective on what constitute research domains.

Table 2 Top journal subject categories (with ten or more publications)

Subject category	# Records
Information Science & Library Science	38
Computer Science, Interdisciplinary Applications	25
Multidisciplinary Sciences	25
Planning & Development	22
Ethics	21
Business	15
Social Issues	15
History & Philosophy Of Science	13
Management	13
Medical Ethics	12
Social Sciences, Biomedical	12
Law	11
Social Sciences, Interdisciplinary	11
Chemistry, Multidisciplinary	10
Engineering, Multidisciplinary	10
Medicine, Legal	10

Source: Author analysis of 199 articles excerpted from WOS SSCI/AHCI, retrieved September–October, 2007

papers (43%) have zero cites, while 60 (24%) have a single citation. At the other extreme, a paper by Meyer (2000) examining linkages between patents and research papers in nanoscale technologies garners 55 WOS citations. This is followed by papers with 29, 20–22 (4 papers), 10–16 (8 papers), and 5–9 (22 papers) citations. Table 3 lists the most cited of these articles. Journals which are prominent for highly-cited peer-reviewed nanotechnology-related social science articles include *Scientometrics* (25 articles, 111 total citations), *Research Policy* (24 articles, 112 total citations), and *Science Communication* (13 articles, 61 total citations).

The second citation type—backward citations—comprises references to other works cited by the articles in our dataset. Importantly, these references are not restricted to WOS records, but can include a range of sources, including articles, books, book chapters, governmental reports, and other publications. Such references within articles can be used as measures of the knowledge sources and intellectual influences that authors draw upon, again with appropriate caution about how citations to reference sources should be interpreted (Moed 2005). In the balance of this section, we focus our analysis on these backward citations of nanotechnology-related social science articles to other knowledge sources. Eighty-four percent of our database, or 260 articles, include cited references. After grouping similar citations via an automated VantagePoint function, followed by a manual review and cleanup, we are able to identify the most cited references among all the cleaned references. We will examine how these cited references have changed over time based on (1) the most highly-cited researchers, and (2) subject categories of cited articles' journals.

First, we examine the most highly-cited authors referenced by at least ten of the nanotechnology-related social science articles in our dataset. The most highly-cited authors are of greatest interest in terms of understanding the underlying dimensions behind these citations. Figure 1 presents a co-citation map of these authors. A Multi-Dimensional Scaling (MDS) map was generated based on the degree of association (that is, being cited

Table 3 Nanotechnology-related social science articles: most frequently cited references (with 20 or more citations)

Title	Author(s)	Source	Publication Year	Cites
Forward citations: most cited nanotechnology-related social science articles (N = 308)				
Does science push technology? Patents citing scientific literature	Meyer, M	Research Policy	2000	55
Patent citations in a novel field of technology—what can they tell about interactions between emerging communities of science and technology	Meyer, M	Scientometrics	2000	22
Multidisciplinarity, interdisciplinarity, and patterns of research collaboration in nanoscience and nanotechnology	Schummer, J	Scientometrics	2004	22
Nanotechnology—interdisciplinarity, patterns of collaboration and differences in application	Persson, O; Meyer, M	Scientometrics	1998	21
Nanoscience and nanotechnology on the balance	Braun, T; Schubert, A; Zsindely, S	Scientometrics	1997	20
Backward citations: most cited publications in nanotechnology-related social science articles (N = 8,363)				
Engines of creation: the coming era of nanotechnology	Drexler, K.E.	Anchor Books	1986	45
Nanoscience and nanotechnologies: opportunities and uncertainties	Royal Society	UK	2004	30
Why the future doesn't need us	Joy, B	Wired	2000	26
Converging technologies for improving human performance	Roco, M and Bainbridge, WS	J Nanoparticle Research, Springer	2002+	24
Societal implications of nanoscience and nanotechnology	Roco, M and Bainbridge, WS	Springer	2001	21
Multidisciplinarity, interdisciplinarity, and patterns of research collaboration in nanoscience and nanotechnology	Schummer, J	Scientometrics	2004	21

Source: Author analysis of 308 articles excerpted from WOS SSCI/AHCI and Scopus, retrieved September–October, 2007

by the same articles).[6] Larger nodes reflect more citations. Heavier links reflect a greater degree of association, based on a Path Erasing Algorithm. Absence of a link does not mean zero co-citations, rather fewer co-citations. This is a visualization intended to gain perspective on the affinities reflected—location along the axes has no meaning; nearness tends to reflect association. There is no "right" map—the underlying many-dimensional associations are collapsed into a two-dimensional representation here. Recognize also that Web of Science (SSCI and AHCI) only gives the first cited author, so co-author information is absent.

The map suggests eight primary dimensions in the cited literature. These dimensions represent the major bodies of knowledge and authority that have been drawn upon by

[6] The VantagePoint version 5.1 autocorrelation function was used to generate this map. VantagePoint software is described at: http://www.theVantagePoint.com.

authors writing about nanotechnology in society. They are presented below. The labels reflect our reading of the core concerns of each dimension. Although there is some overlap, with certain authors cited across more than one dimension of the literature, we have located individual authors in the dimension where they receive most references (with major links to other dimensions as shown in Fig. 1). Additionally, while the most frequently cited first author names are given, these authors may co-publish with others who are not listed, except in examples of cited works indicated in the text below. Where examples of cited works are listed in the text, these are illustrative and do not necessarily represent the full body of cited works produced by that author and colleagues. The eight dimensions in the literature cited by articles related to nanotechnology in society are:

- *Technology trajectories and implications*—assessments and projections of how nanotechnology will emerge, including issues of convergence and the significance of

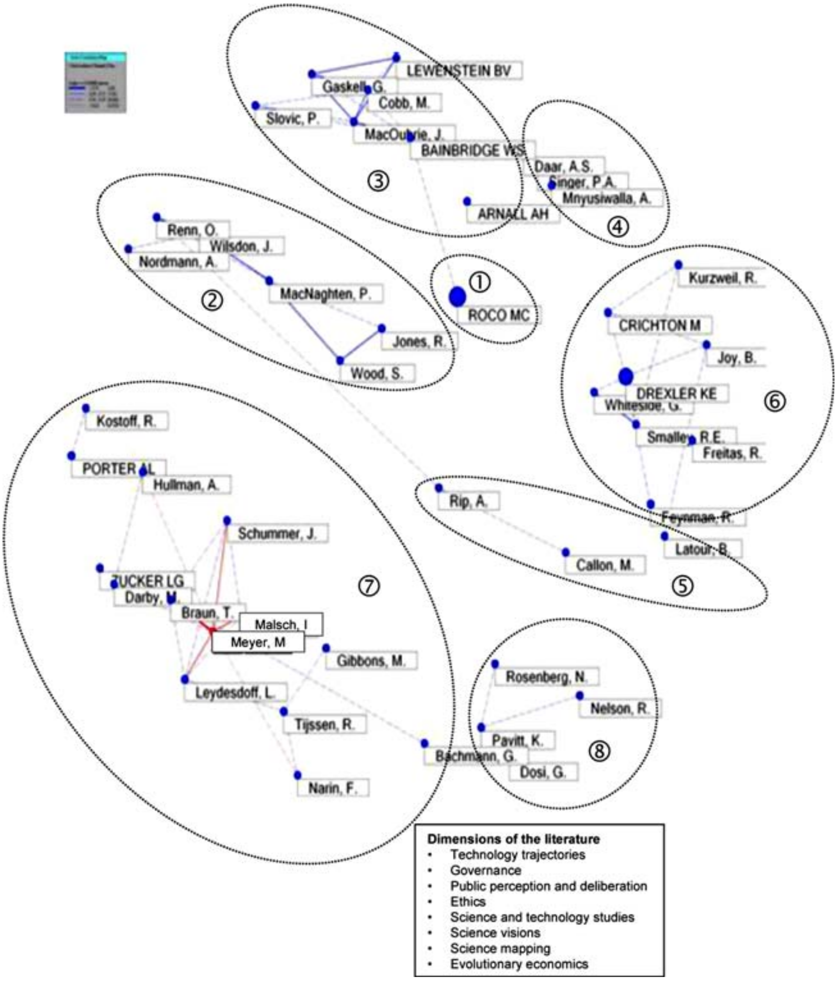

Fig. 1 Co-citation map of authors most cited by nanotechnology social science articles

addressing social concerns. M.C. Roco, a senior advisor for nanotechnology with the US National Science Foundation and a mechanical engineer, is a centrally-cited author, including publications co-authored with colleagues (Roco and Bainbridge 2001, 2002a, b; Roco 2001, 2003).

- *Governance*—dealing with concerns about the governance of nanotechnology and approaches to risk, contrasts between different countries, and the role of social science in informing policymaking. The key authors cited in this literature include individuals with training in philosophy (A. Nordmann, J. Wilsdon), sociology, social psychology, and behavioral sciences (O. Renn, P. Macnaghten, S. Wood), and physics (R. Jones). (Nordmann 2004; Jones 2004; Renn and Roco 2006; Wood et al. 2003; Macnaghten et al. 2005; and Wilsdon and Willis 2004.)
- *Public perception and deliberation*—emphasizing issues related to nanotechnology and public opinion, public attitudes, the framing of concerns, trust, and problems of public deliberation. Key authors cited by this literature include sociologist W.S. Bainbridge, political scientist M. Cobb, social psychologist G. Gaskell, experts in science communication J. Macoubrie, B.V. Lewenstein, and P. Slovic, and environmental science and policy analyst A.H. Arnall. (Bainbridge 2002; Cobb and Macoubrie 2004; Gaskell et al. 1999; MacOubrie 2002; Lewenstein 2004; Slovic 1993; and Arnall 2003.)
- *Ethics*—addressing questions related to the exploitation of nanotechnology including malevolent uses, impacts on equity, abilities to control new technologies, and moral principles for decision-making. Key authors cited by this literature include A. Mnyusiwalla, A.S. Daar, and P.A. Singer who write from a medical ethics and public health perspective (Mnyusiwalla et al. 2003).
- *Science and technology (S&T) studies*—probing what are, or should be, the underlying matters of concern in the development of nanotechnology, including how nanotechnology objects should be described and conceptualized and how nanotechnology fits within broader projects to use science and technology for political, economic and national ends. Key authors cited by this literature include sociologists of science B. Latour and M. Callon, and philosopher of science and technology A. Rip (Latour 2004; Callon 1991; and Rip et al. 1995).
- *Science visions*—comprising references to R. Feynman's early ideas about the possibilities of atom-by-atom manipulation (Feynman 1960) to the views of—and debates among—scientists and technologists such as K.E. Drexler, R.E. Smalley, B. Joy, R. Freitas, G. Whiteside, R. Kurzweil about nanotechnology's prospects, benefits and drawbacks (Drexler 1986; Smalley 2001; Joy 2000; Freitas 1999; Whiteside 2001; and Kurzweil 1999). Also referenced in this group are fictional and science-fictional narratives of nanotechnology applications and their dangers, most prominently (in terms of citations) by M. Crichton (2002).
- *Science mapping*—covering references within the nanotechnology-related social sciences literature to such topics as patterns of collaboration, measures of interdisciplinarity, indicators of performance (including publications and patents), emergence of networks, exchange of knowledge, and development of innovation. Key authors cited by this literature have expertise in the quantitative measurement of science and technology activities, technology assessment and forecasting, economics, sociology, and policy, including J. Schummer, M. Meyer, T. Braun, I. Malsch, A. Hullman, L. Leydesdoff, A.L. Porter, R. Kostoff, M. Darby, F. Narin, M. Gibbons, G. Bachmann,

R. Tijssen, and L.G. Zucker (Schummer 2004; Meyer 1998; Braun et al. 1997; Malsch 1997; Hullmann et al. 2003; Leydesdorff et al. 1994; Porter and Chubin 1985; Kostoff et al. 2006; Darby and Zucker 2003; Narin et al. 1997; Gibbons et al. 1994; Bachmann 1998; Tijssen 2004; and Zucker et al. 1998).

- *Evolutionary economics*—drawing on references to literature that stresses the role of institutions, processes, learning, and interaction in understanding technological change. Key authors cited in this literature include economists R. Nelson and G. Dosi, science and technology policy scholar K. Pavitt, and economic historian N. Rosenberg (Nelson and Winter 1982; Dosi 1982; Pavitt 1984; and Rosenberg 1982).

In some cases, nanotechnology social science authors draw upon generic bodies of knowledge, applying this knowledge to questions related to nanotechnology. In other cases, authors draw upon bodies of knowledge that are more specific to the nanotechnology domain. We examine the role of generalist and nanotechnology-specialist knowledge by classifying the works of the authors in the above eight categories accordingly. We focus on the cited references in the Scopus sample (for which full titles are provided, whereas SSCI/AHCI just gives abbreviated first author and journal information), and classified the references as nanotechnology-related or otherwise. The percentage of citations that draw on nanotechnology-specific knowledge for each of the eight classes are weighted by the frequency with which particular source items are cited, although the unweighted tallies are virtually identical. The percentages of citations involving nanotechnology-specific works are as follows.

- Technology trajectories and implications: 100% nanotechnology-specific
- Governance: 51% nanotechnology-specific
- Public perception and deliberation: 71% nanotechnology-specific
- Ethics: 64% nanotechnology-specific
- Science and technology (S&T) studies: 4% nanotechnology-specific
- Science visions: 83% nanotechnology-specific
- Science mapping: 35% nanotechnology-specific
- Evolutionary economics: 0% nanotechnology-specific

These results indicate that references in the evolutionary economics and S&T studies categories are drawing upon general principles rather than nanotechnology-specific knowledge. Conversely, cited works in the technology trajectories and implications (e.g., Roco) and science visions dimensions draw on more nanotechnology-specialist knowledge. The other areas present a mix.

Figure 2 indicates how these dimensions have changed over time. The figure suggests that in the earlier time periods, nanotechnology-related social science literature drew more heavily on literature from science visions (which includes work by scientists projecting future trajectories for nanotechnology, such as the classic Drexler-Smalley debate about self-assembly (Baum 2003), and popular works of science fiction (such as Crichton 2002). However since 2004, social science literature, particularly science mapping, has come into greater prominence in influencing nanotechnology-related social science research, followed by works about public perception.

We further examine trends in cited works through visualizing how their positioning has changed in the global map of science. We present a visualization that situates the journal subject categories of the cited references within the "map of science" developed by Loet

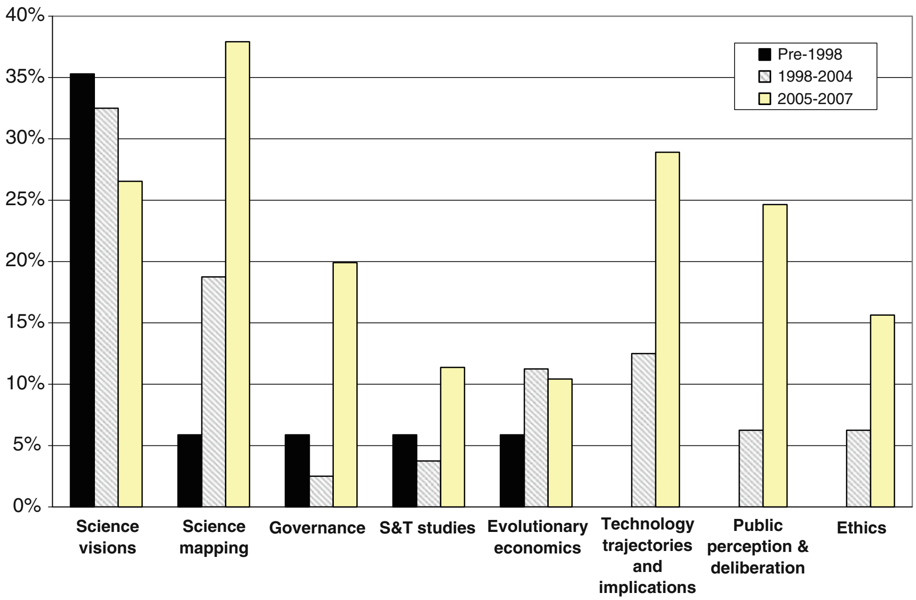

Fig. 2 Trends in citations to key authors by primary categories in the nanotechnology social science literature. *Note*: the Y-axis measures nanotechnology-related social science articles published by period (pre 1998, 1998–2004, 2005–2007) that have a cited reference to an author within one of the eight primary dimensions of cited literature defined in Section "Citations" as a percentage of the total number of nanotechnology-related social science articles in the database for that given time period. Total number of publication records = 308. Total citations to primary category authors = 455

Leysdesdorff, Ismael Rafols and colleagues in 2008 (Leydesdorff and Rafols 2009; Rafols and Meyer 2009). The map of science is based on a decomposition of the relationship of cited to citing articles aggregated to Thomson Reuters' ISI journal subject category level.[7] The resulting map of science represents 244 journal subject categories[8] and is drawn in Pajek.[9] Comparison of the maps before and since 2005 in Figs. 3 and 4 indicates that citations of social science works in the social science domains of the maps are more prominent in more recent periods than before 2005. Of course, there are more articles in the 2005–2007 period, and there continues to be robust citing of scientific literature in the map of science. Still, the maps provide a further indication of the growing importance of the body of social science literature developing around the study of the emergence of nanotechnology.

[7] There are other maps of science based on more detailed data structures, see for example, Boyack et al. 2005; and Scitech Strategies, Inc., 2008.

[8] This reflects analysis of the SSCI cited references using thesauri that associate journal names to the Subject Categories. This was enhanced by manual assignment of Scopus reference source names, and consolidation with the SSCI tallies.

[9] For more information on Pajek network analysis software, see http://pajek.imfm.si/doku.php?id=pajek.

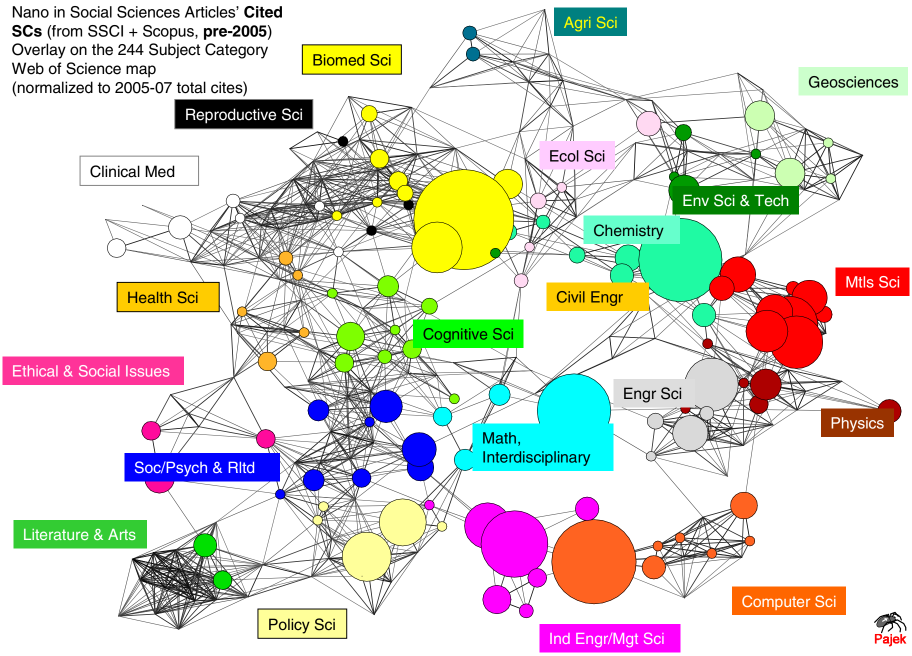

Fig. 3 Cited references by nanotechnology-related social science articles in the map of science prior to 2005

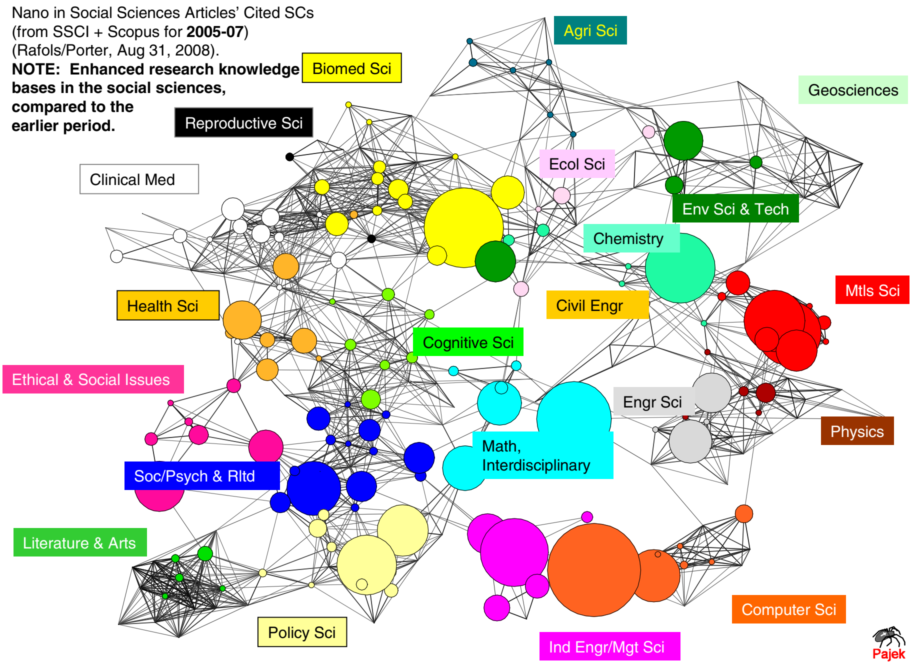

Fig. 4 Cited references by nanotechnology-related social science articles in the map of science 2005–2007

Conclusions

In emerging technologies, there is a growing emphasis on the inclusion of social science perspectives. This is evident in the policies in the US such as the 21st Century Nanotechnology Research and Development Act, where consideration of the societal impacts of nanotechnology is mandated, and in NSF's investment in NSEC research centers that examine nanotechnology in society. These initiatives raise questions about how the social science literature has responded to such initiatives, including how and from where social science knowledge related to nanotechnology is sourced. Our analysis and findings provide a basis for assessment of the additionality provided by support to social-science research into the implications of nanotechnology development.

To explore such questions about scholarly activity and sources, we developed a dataset of nanotechnology-related social science articles. The development of the dataset involved experimentation and iteration through the use of keywords, merging of datasets from two different sources, and exclusion of out-of-scope publications. It should be noted that the nanotechnology-related social science dataset is several orders of magnitude smaller that the nanoscience and engineering dataset. Still, considerable growth is noted, particularly since 2005.

One of the important findings in nanotechnology-related social science according to this dataset is the early-stage citing of science literature. This finding suggests that in examining emerging technologies, such as nanotechnology, there is an initial impetus among social scientists to review and place greater weight on literature produced by natural scientists and engineers, even as those scientists and engineers are writing broadly about their anticipations of the impacts of their discoveries. To an extent, this finding reflects the lack of a social science literature specific to the emerging technology in its early phases, although it also reflects the point that natural scientists and engineers often make early written forays in predicting the development of new technologies. These early writings, which may in part be associated with efforts by some of these scientists to establish their new technological field and secure support for it, may attract significant attention and become cited as reference points in subsequent debates about the technology and its development and implications.

Since 2005 (which is shortly after significant increases in public support for nanotechnology-related social science in the US and elsewhere), we see stronger development and integration of social science literature around this emerging technology area. Moreover, this growth is led by new research conducted using a variety of methodological approaches, including quantitative measurement of output (using bibliometrics), large-scale surveys of scientists and public opinion, and analyses using approaches grounded in philosophy, economics, sociology, and policy analysis. The research forms a series of additional clusters of nanotechnology-specific knowledge, especially in clusters related to public perception and deliberation, ethics, governance, and science mapping. These are added to new nanotechnology-specific sources related to technology trajectories and science visions, and to existing general sources drawn from most of these clusters, including but not limited to evolutionary economics, to provide an interdisciplinary and cross-cutting knowledge base that is accessible to, and sourced by, social scientists writing about the societal implications of nanotechnology.

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