The Journal of Technology Transfer
© Springer Science+Business Media, LLC 2008
10.1007/s10961-007-9076-5

Mapping the nanotechnology enterprise: a multi-indicator analysis of emerging nanodistricts in the US South

Jan Youtie[1] and Philip Shapira[2, 3]

(1) Enterprise Innovation Institute, Georgia Institute of Technology, Atlanta, GA 30332-0640, USA

(2) School of Public Policy, Georgia Institute of Technology, Atlanta, GA 30332-0345, USA

(3) Manchester Business School, University of Manchester, Manchester, M13 9PL, UK

Jan Youtie (Corresponding author)
Email: jan.youtie@innovate.gatech.edu

Philip Shapira
Email: pshapira@gatech.edu

Published online: 25 January 2008

Abstract Nanotechnology has attracted significant research, funding, and policy activity in recent years in the US and many other countries. Of particular interest are the locational characteristics of this emerging technology. This study examines the emergence of nanotechnology in the US South to explore questions of regional standing and spatial trajectory, using an exploratory multi-indicator approach. Our research employs an array of 10 indicators of knowledge generation, human capital, R&D funding, and patenting, to uncover developments, clusters, and linkages in nanotechnology emergence. Results indicate that although there is nanotechnology activity in every state in the US South, this activity agglomerates in a few locations. One emerging nanodistrict (North Carolina's Research Triangle) has prior strengths in high technology research and commercialization, especially based on biotechnology; but other districts (e.g., Oak Ridge Tennessee and Atlanta, Georgia) that have strengths in certain aspects of the nanotechnology research ecosystem have weaknesses in commercialization. The study illustrates how multi-indicator approaches can be developed from existing databases, using customized search techniques, and how the insights from multi-indicator measurement can be used to provide insights for research and innovation policy.

Keywords Indicators - Nanotechnology - Regional clusters

JEL Classifications 0180 - 0300

1 Introduction

Indicators and measures for emergent technologies frequently focus at the national level (OECD *2006*; World Economic Forum *2006*), with assessments of where a country leads (or lags) influential in national discussions of research and innovation policy. Among factors that have stimulated the widespread use of national technological indicators are increased global competition (and hence a desire to track standing and identify performance gaps), and the availability of data in electronic form (allowing multiple national indicators to be tracked and comparative analyses performed). At the same time, there is growing interest in the development of emergent technology indicators and measures at the *regional* (i.e. sub-national) level.

The interest in improving regional indicators is underpinned not only by factors similar to those just noted for the national scale, but also by greatly increased scholarly and policy attention in recent years to the role of localities in technological development. Concepts such as regional innovation systems, the learning region, regional clusters, and the innovative milieu have been advanced to explain the development of emergent technologies in certain locales (see Cooke et al. *1997*; Morgan *1997*; Porter *2000*; Moulaert and Sekia *2003*). Of course, there continues to be disagreement about the relative importance of spatial proximity in technological advancement (for example, see Boschma *2005*, on the influence of local linkages versus extra-regional relationships). Additionally, there is debate about which specific local factors and elements are most significant in a region's technological growth. Various studies examine how knowledge spillovers, tacit exchanges of knowledge, scientific and technical capabilities in the local labor market, and complementary industries make certain regions focal points for the development of high technology industries (Audretsch and Feldman *1996*; Rosenfeld *1992*; Aharonson et al. *2004*). Zucker et al. (*1998*) report that startup biotechnology firms are apt to locate near universities where star scientists conduct research. Agrawal and Cochburn (*2003*) emphasize the importance of large anchor tenant firms in the location of patents in medical imaging, neural networks, and signal processing industries. The location of venture capital funding has been found to affect the spatial concentration of startups in emergent industries such as biotechnology (Powell et al. *2002*).

Interest in the regional dimension of technological development has stimulated the publication of regional innovation indicators. In 2004, a chapter on science and technology at the state level was introduced into the National Science Foundation's *Science and Engineering Indicators*, using 24 state indicators; this was expanded to 42 state indicators in 2006 (National Science Board *2004*, *2006*). Similarly, the European Union has expanded its measurement activities to include a regional innovation scoreboard (Hollanders *2007*). The indicators produced by such efforts are broad. For example, they include state and regional measures of elementary and high school performance, students in higher education, workforce qualifications, R&D spending, article publication, patent applications, high technology output, and venture capital funding. Although these measures are useful for regional comparisons of innovation environments, such measures are too wide-ranging to capture regional developments in any specific emergent technology. On the other hand, regional micro-level studies of particular emergent technologies tend to focus just on one or two indicators, typically publications or patents. There are exceptions. For example, in the nanotechnology field, Heinze (*2006*) also assesses investments, public attention cycles, inter-organizational networks, and prize winners in addition to publications and patents. We suggest a multidimensional perspective that furnishes a richer, more nuanced view of the dynamics of nascent technologies.

In this paper, we probe nanotechnology research and commercialization at a regional level using multiple indicators. In this process, we seek to validate the feasibility and usability of particular indicators. Our study is further designed to illustrate how multidimensional indicators can be used to inform policymaking. In geographical terms, we concentrate on the US South and the likely spatial trajectory of the nanotechnology sector in the region. A key question is whether nanotechnology is like—or will be like—prior technologies in the way it develops. Nanotechnology may be regionally path dependent, influenced by the historical clustering of research centers, high tech industries, and complementary assets, but there is debate as to which particular path will be followed. Mangematin (*2006*) argues that large public and private research facilities might be important in attracting nanotechnology-related firms much as was the case with microelectronics. In contrast, Davenport and Daellenbach (*2006*) point out that nanotechnology activity in New Zealand, not a traditional spot for an agglomeration of emergent technologies, has taken place around publication networks rather than around 'bricks and mortar.' Another perspective suggests that nanotechnology might be more like biotechnology, apt to be spread across multiple geographic locales depending on their research, human capital, or other attributes. Zucker and Darby (*2005*) observe that the top regions based on counts of nanotechnology publications include many which also are leading US biotechnology centers.

This debate has important ramifications for the US South. More than 65 million people, or about 22 percent of the US population, live in the Southern Growth region—the 13 contiguous US states that belong to the Southern Growth Policies Board.[1] Regional per capita income in the South is now close to the US average (compared to about one half of the US average in 1930, see Shapira *2005*). Yet, despite population, employment and income growth, the South is still not a well-established region of innovation (Doron et al. *2004*). If nanotechnology follows a similar trajectory to biotechnology, then the South as a whole may not be greatly favored. Except for North Carolina's Research Triangle, few Southern locations have any prominence in biotech (Cortright and Mayer *2002*). If nanotechnology commercialization gravitates to regions with large-scale research facilities, this has mixed implications, since while the South has accumulated public research capabilities, large-scale private research is weak. On the other hand, if nanotechnology emerges as a broadly applicable, general purpose technology (Youtie et al. *2007*), will Southern companies in existing as well as new high technology industries be able to commercialize nano's diverse applications? Can state leaders in the South hope for a technology leap by finding new opportunities in nanotechnology? Or, will nanoindustrialization concentrate in just a few US metropolitan areas, such as Silicon

Valley and Boston, which have already well-honed innovation capabilities to rapidly commercialize research?

In the following, we discuss the methodology used to identify multiple indicators of nanotechnology research and innovation and present our findings. Based on measurable research, human capital, and commercialization activities to date, our study will show that much of the US South has little possibility to develop any significant nanotechnology industry. However, a few clusters of nanotechnology-related research and innovation activity are emerging in specific Southern locations. The potential of these nascent nanodistricts varies according to which of the multiple indicators are stressed. In our conclusions, we consider the implications of these results, both for the further development of multiple emergent technology indicators and for regional innovation policy.

2 Methodology

Nanotechnology involves the manipulation and control of matter at the scale of 1–100 nanometers (one nanometer = one billionth of a meter) to understand and create materials, devices and systems with novel properties and functions due to their small structure (National Nanotechnology Advisory Panel *2005*, p. 7). There are already hundreds of products on the market which depend on or are enhanced by nanotechnologies, ranging from advanced electronics to paints, cleaners, cosmetics, textiles and sports equipment (Project on Emerging Nanotechnologies *2007*). In future years, nanotechnology is foreseen as enabling advances in materials, electronics, life sciences, and other fields, with implications not only for new products but also human performance, work organization, and business models (Roco *2004*; National Nanotechnology Advisory Panel *2005*).

The field of nanotechnology is an evolving research domain which covers multiple scientific disciplines (including physics, chemistry, biology, biotechnology, engineering, electronics, and materials). A fundamental building block in our attempt to use multiple indicators to measure nanotechnology emergence was the identification of an appropriately detailed operational definition of nanotechnology that can capture the diversity of the domain. There are several available search term definitions and approaches (see Porter et al. *2007*). We drew upon a search term definition of nanoscience and nanotechnology used in the Project on Creative Capabilities and the Promotion of Highly Innovative Research in Europe and the United States (CREA, see Heinze et al. *2007*). In the CREA project, 16 search terms were combined to identify nanotechnology publications and patents; simple measurement terms (e.g. nanomet* or nanosecond*) or chemical symbols (e.g. sodium nitrate: $NaNO_3$) were excluded.[2] This definition goes beyond the simple search terms (e.g. nano*) used in other nanorelated research. We used this search term in the identification of nanopublications and patents, and also adapted it for applications to other databases. In a few cases, we had to revert to simple definitions (such as nano*) because the search application associated with the databases could not accept a complex search term. In such cases, we further reviewed results to ensure records were in-field.

Our conceptual framework emphasized the importance of knowledge investments in the emerging nanoscience and nanotechnology domain, including investments in research and development (R&D), human capital, intellectual property, and corporate capabilities. These are building blocks for scientific development and commercial application. We identified 10 indicators to capture aspects of these building blocks. Our indicators were organized into four groups: knowledge generation, human capital, R&D funding, and patenting (see Table 1).

Table 1 Indicators used to measure nanotechnology in the US Southern Growth region

Category	**Indicator (with source and reference years)**	**Measures (1995–2004) Southern Growth region (% of US)**	**Specialization index[a]**
Knowledge generation	1. Nanotechnology publications based on author location (SCI, 1995–2004)[b]	5,604 (20.2%)	0.86
	2. Institutions with clusters of primary researchers in nanotechnology (SCI, 1995–2004)[b]	Southern institutions with 3 or more primary researchers = 67	
	3. Co-authorship linkages in nanotechnology (SCI, 1995–2004)[b]	33% (elsewhere in US)	
		18% (outside of US)	
Human capital	4. Highly cited researchers in nanotechnology (SCI, 1995–2004)[b]	111 (18.2%)	0.78
	5. Editors of nanotechnology journals (22 nano-relevant journals, 2005)[c]	21[d] (10.3%)	0.44
	6. Doctoral dissertations in the nanotechnology field (Dissertation Abstracts, 1995–2004)[c]	577 (15.9%)	0.67
	7. Prize winners in the nanotechnology field (CREA database of nano-relevant prizes, 1995–2004)[e]	9 (8.0%)	0.94
R&D funding	8. Nanotechnology-related National Science Foundation Awards (NSF Awards, 1995–2004)[c]	$337.4 million (16.9%)	0.72

Category	Indicator (with source and reference years)	Measures (1995–2004) Southern Growth region (% of US)	Specialization index[a]
	9. Nanotechnology-related small businesses innovation research awards (SBIR/STR awards, SBA Tech-Net, 1995–2004)[c]	$77.9 million (15.6%)	0.70
Patenting	10. Patenting in the field, including both individual inventors and companies (USPTO, 1995–2004)[f]	1,015 (8.5%)	0.36

[a]The index of specialization normalizes the indicators for the Southern Growth region by dividing the metrics for the Southern region by 2004 population estimates from the Census Bureau (per million population), then comparing the resulting ratio to the same ratio for the US as a whole (i.e., compared with the US, if the index = 1 then the Southern region performs at the same level, if the index <1 then the Southern region has a lower performance, and if the index >1 then the Southern region has a higher performance)

[b]SCI = Science Citation Index, Thomson Scientific Web of Science. For further details, including discussion of bibliometric definition of nanotechnology, see Heinze et al. (2007)

[c]Refer to discussion in text of article

[d]In 2005

[e]CREA = Project on Creativity Capabilities and the Promotion of Highly Innovative Research in Europe and the United States, see Heinze et al. (2007) for discussion of methodology to identify nanotechnology prize winners

[f]USPTO = United States Patent and Trade Mark Office. See Heinze et al. (2007) for discussion of definition of nanotechnology

Knowledge generation was measured based on nanotechnology-related publications by authors that appear in the Science Citation Index (SCI) database, accessed through Thomson Scientific Web of Science. Nanotechnology publications were identified using the CREA search terms for records published between 1995 and 2004 (inclusive). Three indicators of knowledge generation were examined. First, the location of all authors was reported. Second, institutions with clusters of three or more primary researchers were profiled to represent the potential to generate more knowledge (through scale economies) or to develop in-depth specializations (compared with institutions with one or two isolated authors). The primary researcher is defined as the first author of a publication. Although the first author does not always make the greatest contribution to the research, we do not have additional information that would allow an improvement in distinguishing primary authors. Third, co-authorships—defined as a publication with more than one author based on the authors' institutional affiliations—were used to measure the extent to which Southern Growth states, institutions and scholars were integrated into the broader national and international research communities.

Four human capital indicators were included: highly cited researchers, nanotechnology journal editors, doctoral dissertations, and prize winners. Citation measures are not without bias, in that older publications and more senior researchers have higher probabilities of garnering citations; in some cases there are ‘negative’ citations where work is refuted. However, in general, we considered that researchers with high numbers of aggregate citations have greater influence in their field. Our analysis focuses on the citations of the first author because of ease of connection to an institution and geography. We also identified editors of nanotechnology related journals. Editors serve as gatekeepers for the publications of ideas in the field and represent a group distinguished by the quality of their scientific record (Braun et al. *2007*). To create a list of nanotechnology journals, two scholarly portals and a nomination process (undertaken for the CREA project) were used.[3] These sources resulted in a validated list of 22 significant journals in the nanotechnology field. Our analysis focused on current nanotechnology editors (as of 2005). Doctoral dissertations represented the ability to produce new scientists and engineers as well as serving as a signal for where leading research is taking place, even though many doctoral graduates will migrate to other locales to take-up faculty or research positions. All abstracts with references to “nano” in the title or abstract of the doctoral dissertation were included.[4] We identified scientific prize winners as a selective measure of independently-reviewed high scientific quality and a proxy for ‘star scientists’ (Zucker et al. *1998*). Through expert listings and a nomination process (undertaken for the CREA project), we identified a list of nanotechnology-related prizes. Except for the Feynman Prize, which is for nanotechnology research, many other prizes awarded for nanotechnology research excellence are not dedicated solely to the nano field. The relationship of the prize and prize winner to nanotechnology was further validated through web searches, curriculum vita screening, and publication data filtering.

Two R&D funding indicators were profiled: awards from the National Science Foundation (NSF), using its ‘AwardSearch’ database; and Small Business Innovation Research (SBIR) or Small Business Technology Transfer (STTR) program awards from the Small Business Administration’s Tech-Net database. We were not able to analyze venture capital funding, but we note that the SBIR program has been found by Lerner (*1999*) to have a positive effect on high technology firms’ ability to procure venture capital. Entries that referenced “nano*” were extracted, and then reviewed to confirm they were in-field. SBIR figures represent qualified businesses at the time of receipt of the funds as it was not confirmed whether SBIR award recipients were still in business or still small with fewer than 500 employees.

As a measure of innovation, we used patents. We acknowledge that patents are only one measure of innovation, and that not all patents will be commercialized. However, patent awards do represent an independent source of data on inventions which are new, non-obvious, and have the potential to be applied. Using the CREA search term, we identified patents, including their inventor and assignee locations, awarded by the US Patent and Trademark Office (USPTO).

Our database searches (except for editors) covered the period 1995–2004 (inclusive). This captured a 10-year period of recent knowledge activity, which is appropriate for an emerging field such as nanotechnology. It should be noted that the databases used for the analysis were intended for other purposes, mostly to look up individual records rather than derive aggregated data for regionally oriented indicators. The databases do have errors in the completeness of geographical identifiers. Where possible, these errors were corrected. Nevertheless, some errors may remain in the analysis. These errors are not expected to be systematic. Thus, while absolute counts should always be regarded as approximations, it is anticipated that these errors will not significantly change the relative positions of particular states or institutions.

---

3 Findings

Overall, the Southern region is less specialized than the nation on every one of the 10 indicators of nanotechnology studied (Table 1). But within this, there are important variations. The knowledge generation measures showed that the Southern region has a significant presence in nanotechnology science. Southern researchers were associated with 5,604 SCI publications from 1995 to 2004, or about one-fifth of all US nanotechnology publications – lower than, but not too different from, the region's US population share. There were 2,885 different researchers from the Southern region associated with these publications. The region had 243 institutions with at least one nanotechnology publication based on the location of the first author, of which 67 of these institutions had three or more different researchers. Four Southern institutions—Georgia Tech, the University of North Carolina, Oak Ridge National Laboratory, and North Carolina State University—were among the top 25 US institutions nationally by number of nanotechnology publications during the study period. A further 20 Southern universities and laboratories were among the top 100 US institutions in terms of number of publications.

We examined the interconnectedness of nanotechnology research in the Southern Growth institutions. Thirty-three percent of the nanopublications with an author from an institution in the Southern region also had a co-author somewhere else in the US. Eighteen percent of these Southern publications had a co-author at an institution somewhere else in the world. Three institutions played a critical role in this inter-regional network: Oak Ridge National Laboratory, Georgia Tech, and North Carolina State University. These three institutions also had the most publication-based links with other institutions within the region. Of these, two institutions—Georgia Tech and Oak Ridge National Laboratory—are among the top 20 institutions in the US based on the number of nanopublications. By examining multi-institutional co-authored publications and overall publication scale, we found that the leading hubs of US activity were the University of California at Berkeley, the University of Texas and Stanford University. Oak Ridge and Georgia Tech have co-author relationships with researchers at these three universities, as well as with many researchers at the next set of institutions, but they appear as important players rather than as central focal points.

On human capital measures of nanotechnology, the Southern Growth region demonstrated varying levels of performance. Nanotechnology-related research garnered prizes for 113 scholars in the US (1995–2004). Only nine of these were in the Southern Growth region. The region faired better when gauged against the highly cited primary researcher benchmark. Among the 1,000 most highly cited primary researchers in nanotechnology in the world, there were 611 in the US in the 1995–2004 time period. The Southern Growth region housed 111 of these researchers or 18 percent of the US total. For the editorial board 'gatekeeping' indicator, the Southern Growth region was again less strong. It accounted for only 10 percent or 21 of the more than 200 individuals who served as editors or on editorial boards for the 22 nanotechnology journals that were found to have this function. The region demonstrated a more prominent position regarding dissertations with some reference to 'nano*' in their title or abstract. Nearly 16 percent of such dissertations—or 577 theses—were reported at an institution in the region.

The Southern region's position on the two R&D indicators examined in this analysis is relatively promising. NSF's AwardSearch application produced 4,500 grants to US principal institutions comprising about two billion dollars of funding in the nanotechnology area from 1995 to 2004. The Southern Growth region had 120 organizations that received NSF awards in the nanotechnology area. These institutions received 17 percent of the dollars and 18 percent of the grants. For nanorelated SBIR awards to businesses, nearly 15 percent of SBIR or STTR awardees, and 16 percent of the aggregate dollars, were located in the South.

However, patenting is a serious weakness for the region. Based on a USPTO search for the 1995–2004 time period, only 8.5 percent (1,015) of nanotechnology-related patents (including government-owned nanopatents) had assignees or inventors located in the Southern Growth states. In general, the number of patents *assigned* to Southern Growth states was low compared to the nation. There were 0.6 assignees to every nanotechnology inventor in the Southern region compared to 0.7 assignees per inventor nationally ($p < .05$). In other words, there is some 'leakage' as inventor research patented in the region is assigned to organizations outside of it.

However, to fully understand the picture of emergent nanotechnology development in the South, there is a need to go below the broad regional perspective, since significant intra-regional differences are evident. Within the region, clusters appear on both the research and innovation side (Fig. 1). Four potential nanodistricts lead in terms of research publications and patents: the Research Triangle area in North Carolina; Atlanta, Georgia; Oak Ridge Tennessee; and a poly-nucleated district across Virginia. These four regions dominate nanotechnology activity in the Southern region, although there are a few other nascent clusters, such as the area around the University of Alabama in Birmingham, that might form additional nanodistricts in the future.

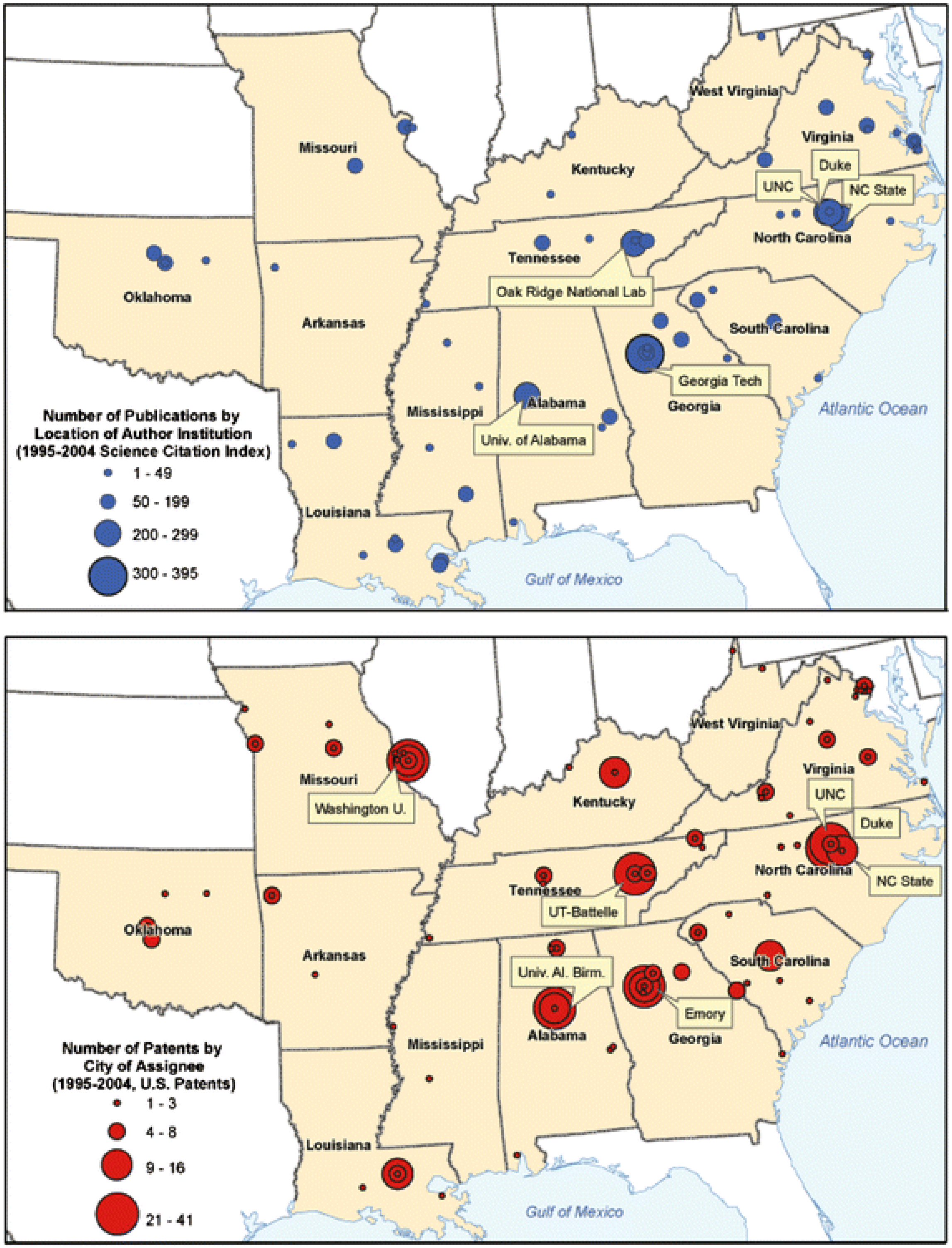

Fig. 1 Publications and Patents, Southern Growth region, 1995–2004. *Notes*: [a]Number of publications at institutions with clusters of three or more different first authors. Location of first author at time of publication is presented. Institutions with 200 or more first authored publications are labeled. Source: Authors' analysis of Science Citation Index, Thompson Scientific Web of Science, 1995–2004, based on nanotechnology definition in Heinze et al. 2007; [b]Number of patents granted by city of assignee. Assignees with 16 or

more patents are labeled. Source: Authors' analysis of USPTO patents granted, 1995–2004, based on nanotechnology definition in Heinze et al. *2007*

North Carolina is ahead of all other Southern states on each of the 10 nanotechnology indicators. Its position is driven by the cluster around the Research Triangle. The three Research Triangle universities (Duke University, the University of North Carolina at Chapel Hill, and North Carolina State University) are consistently among the top in the region on publications, prize winners, highly cited researchers, nanotechnology journal editors, and doctoral dissertations granted (See Table 2). However, although these institutions are strong, they are not among the very top with prominent connections to the dominant and leading national institutions. We emphasize that this is an aggregated observation, since there are individual researchers at each institution who have garnered international acclaim in particular areas of nanotechnology.

Table 2 Nanotechnology district indicators, Southern Growth region (leading states)

Category and indicators		**Leading states**			
		North Carolina	**Georgia**	**Tennessee**	**Virginia**
Leading region in the state		Research Triangle	Atlanta	Oak Ridge	DC Suburbs
Knowledge generation					
Publications	Total number	1,134	836	826	797
	Number for leading institutions	UNC (285) NCSU (277)	GT (395)	ORNL (284)	
Publications with co-author elsewhere in the US	Number for leading institutions	UNC (130) NCSU (119)	GT (147)	ORNL (193)	UVA (103)
Publications with co-author elsewhere in the world	Number for leading institutions	NCSU (100) UNC (73)	GT (93)	ORNL (106)	VCU (61)
Institutions with three or more primary researchers	Total number	10	6	6	11
Human capital					
Highly-cited primary researchers	Total number	30	24	14	11
	Number for leading institutions	UNC (18) Duke (9) NCSU (3)	GT (22)	ORNL (7)	UVA (3)
Editors of nanotechnology	Total number	5	4	1	7
	Number for	NCSU (3)	GT (3)		

Category and indicators		Leading states			
		North Carolina	Georgia	Tennessee	Virginia
journals	leading institutions				
Doctoral dissertations in nanotechnology	Total number	125	95	39	72
	Number for leading institutions	NCSU (57)	GT (75)	UT (20)	UVA (30)
		UNC (51)			VCU (25)
Prize winners in nanotechnology	Total number	4	4	0	1
	Number for leading institutions	NCSU (2)	GT (4)		UVA (1)
		UNC (1)			
		Duke (1)			
R&D funding (millions)					
NSF grants	Total amount	$53.4	$33.8	$26.1	$36.8
	Amount for leading institutions	NCSU ($17.7)	GT ($23.5)	UT ($10.5)	UVA ($9.2)
		Duke ($15.8)		Vanderbilt ($9.0)	VT ($6.5)
		UNC ($11.5)			
SBIR/STTR grants	Total amount	$6.8	$6.5	$5.4	$41.7
Patenting					
Patents (inventors or assignees)	Total number	214	145	120	182
	Number for leading institutions	UNC (41)			
		Duke (21)	Emory (23)	UT-Batelle-ORNL (21)	UVA (12)
		NCSU (16)	GT (17)		

Note: Data sources for period 1995–2004, except for editors (2005). See Table 1.
Institutional codes: UNC = University of North Carolina; NCSU = North Carolina State University; GT = Georgia Tech; ORNL = Oak Ridge National Laboratory;
UT = University of Tennessee; UVA = University of Virginia; VCU = Virginia Commonwealth University; VT = Virginia Tech

Georgia's position in nanotechnology is driven by Georgia Tech. The institution ranks in the top 10 institutions nationally based on number of nanotechnology-related publications by first author, and in the top 20 institutions nationally in numbers of co-authored publications in nanotechnology. It is one of the top three US universities in terms of number of highly cited primary researchers in nanotechnology. Georgia Tech professors have been awarded nanotechnology prizes and have granted more nanorelated doctoral dissertations than any other institution in the region. And it is among the top 25 institutions based on dollar amount of nanotechnology-related NSF grants. On the other hand, Atlanta lacks the strong positioning of other institutions in nanotechnology in the manner of Research Triangle, although Emory University is certainly emerging in important areas. Moreover, there is little private-sector corporate R&D activity in the region, which makes for a weak basis for local commercialization.

The Oak Ridge National Laboratory is also a national leader in nanopublications, institutional clusters, and co-authorship linkages. Following the facilities-based model of emergent technology development, the Laboratory has developed a strong core of user facilities complemented by its scientific and technical scientists and researchers. At the same time, Oak Ridge is a large federal laboratory in a small community. The question is how the laboratory will escape this limitation to leverage its nanotechnology strengths, particularly if it seeks to have an effect on nanotechnology business development in its region.

Virginia ranked above average for the Southern Growth region in knowledge generation and human capital development. However, there are no national players, unlike the research institutions in the other three districts. Likewise, there is no geographic hub to the district; it follows a decentralized model with nodes near Washington DC and the major universities in the state. Virginia is stronger on the commercialization side, particularly with respect to SBIR/STTR awardees. Virginia also has a much higher inventor to assignee ratio of any state in the region, showing robust idea generation capabilities in nanotechnology. There is surely a ‘capital effect’ given the proximate influence of Washington DC and the many federally-oriented R&D organizations in the metropolis, a number of which are located in Virginia.

4 Conclusions

This paper has explored the emergence of nanotechnology at a regional level employing an array of indicators in categories of knowledge generation, human capital, R&D funding, and patenting. The measurement approach targets a specific emergent technology, in contrast to other general regional measures. It also goes beyond the traditional use of publications and/or patents alone to provide a multidimensional perspective on the technology. In particular, we have added to the mix indicators related to prize-winning scientists, journal editors, and dissertation research. Our indicators have been localized toward a region that is often overlooked in national views of emergent technology agglomerations. We acknowledge that our pilot study treated these indicators as separate measures. A future direction would be to undertake statistical testing of these multiple indicators to ascertain complementarity or overlap. This would require a larger database with greater geographical coverage than in this pilot study. But it could allow honing in on fewer indicators of regional emergent technology capability. Other emergent technology indicators also could be conceptualized, for example venture capital or technology licensing.

The results showed that there is a substantial level of nanotechnology-related activity in the US South. The Southern Growth region included 20 percent of all nanotechnology research publications, 18 percent of all highly cited nanotechnology researchers, 16 percent of all nanotechnology doctoral dissertations, and 17 percent of all nanotechnology related NSF grant awards in the United States. At the same time, several weaknesses were highlighted. The region's institutions lacked strong linkages to critical US centers in California and the Northeast. The region also was significantly weak in patenting: 14.8 nanotechnology patents per million in the Southern Growth region compared with 40.9 for the nation. Moreover, a relatively higher share of these Southern Growth patents was assigned to organizations outside the region.

Still, in a few locations in the South, nanodistricts are beginning to emerge. Not surprisingly, the Research Triangle was the strongest region in the South. One explanation is that Research Triangle has been considered a top location for other emerging technologies including IT and biotechnology. Does this positioning of Research Triangle mean that there is a relationship between biotechnology and nanotechnology? And if so, are there lessons from the Research Triangle that can be applied to other regions in the South? On the first question, this analysis cannot confirm an association between biotechnology and nanotechnology based on indicators presented here. Atlanta and Oak Ridge are not nationally recognized centers of biotechnology—for example, Cortright and Meyer (*2002*) classify Atlanta at the median among major metropolitan areas—yet these two Southern Growth clusters hold prominent positions in nanotechnology. Atlanta has become more prominent as a result of the emergence of Georgia Tech and its eminent researchers, who have garnered top rankings as highly cited authors and winners of nanotechnology research prizes. This characteristic suggests that Atlanta's nanodistrict strategy most closely reflects the star scientist model articulated by Zucker et al. (*1998*), with the exception that nanotechnology-related commercialization has yet to develop to any significant extent. One lesson from the Research Triangle that may be applicable to Atlanta is the importance of having multiple strong universities and private sector companies involved in an emerging technological area as opposed to a single dominant institution. Oak Ridge has become more prominent by leveraging the national laboratory to generate nanotechnology activity. Oak Ridge provides some support for the facilities-based model of nanotechnology emergence which Mangematin (*2006*) observed in the Grenoble area, although Oak Ridge lacks Grenoble's population density and concentration of large and small companies. This raises the reservation that facilities alone may not be enough to ensure the emergence of a nanodistrict.

It does seem possible for the South to participate in the development of nanotechnology. But much of the South has little likelihood for a major change in position from nanotechnology. There are a few places that have potential to develop nanodistricts. However, each has weaknesses as well as strengths. Some of these weaknesses *may* be amenable to public or private action, such as the availability of risk capital or support for spin-off technology enterprises. Other weak points, such as population density or the lack of major private R&D labs, may not be addressed in the foreseeable future. Efforts to share information about and to coordinate policies on nanotechnology at the regional level may be helpful, although, there is a need to strengthen the connections of leading institutions in the South with those outside of the region.

Our analysis suggests that nanotechnology *research* clusters can be fostered as a result of public policy and other factors. However, only a few of these research clusters have emerged. The ability to commercialize this research may well be significantly regionally path dependent. The regional structure of existing private firms (incumbents) and private R&D, as well as smaller regional capital pools, are major limiting factors in the US South. While the region has a base of knowledge, human capital, and institutional links in nanotechnology, the extent to which the research, innovation and policy system can address the region's major limiting factors at the nanodistrict level will determine the prospects for the region to host a substantial share of the nation's new nanotechnology industry.

Acknowledgements This paper draws on a study prepared by the authors for 'Connecting the Dots: Creating a Southern Nanotechnology Network,' a Southern Technology Council/Southern Growth Policy Board project funded by the Oak Ridge National Laboratory's Technology Transfer and Economic Development Directorate (Pennock et al. *2006*). Additional analysis was supported through the Center for Nanotechnology in Society at Arizona State University (National Science Foundation Award 0531194). We gratefully acknowledge the assistance of Ajay Bhaskarabhatla, Alexa Stephens, Li Tang, Erin Lamos, John Slanina, and Uttam Malani. We thank Scott Doran and Charity Pennock of the Southern Technology Council for their collaboration and also anonymous reviewers for the improvements they suggested. The views in the paper are those of the authors and should not be attributed to any of the sponsoring organizations.

References

Agrawal, A., & Cockburn, I. (2003). The anchor tenant hypothesis: Exploring the role of large, local, R&D-intensive firms in regional innovation systems. *International Journal of Industrial Organization, 21*, 1227–1253.

Aharonson, B., Baum, J., & Feldman, M. (2004). Industrial clustering and the returns to inventive activity: Canadian biotechnology firms 1991–2000. DRUID Working Paper 04-03.

Audretsch, D., & Feldman, M. (1996). R&D spillovers and the geography of innovation and production. *American Economic Review, 86*(3), 630–640.

Boschma, R. A. (2005). Proximity and innovation: A critical assessment. *Regional*

Studies, 39(1), 61–74.

Braun, T., Dióspatonyi, I., Zádor, E., & Zsindely, S. (2007). Journal gatekeepers indicator-based top universities of the world, of Europe and of 29 countries—A pilot study. *Scientometrics*, *72*(2), 155–178.

Cooke, P., Uranga, M. G, & Etxebarria, G. (1997). Regional innovation systems: Institutional and organisational dimenstions. *Research Policy*, *26*(4–5), 475–491.

Cortright, J., & Mayer, H. (2002). *Signs of life: The growth of biotechnology centers in the US*. Washington, DC: The Brookings Institution.

Davenport, S., & Daellenbach, U. (2006). Building a 'Nano-nation'? The role of the MacDiarmid institute in New Zealand. Workshop on mapping the emergence of nanotechnologies and understanding the engine of growth and development, March 1–3, 2006, Grenoble, France.

Doron, S., Clinton, J., & Barlow, K. (2004). *Not invested here: The 2004 southern innovation index*. Research Triangle Park, NC: Southern Growth Policies Board.

Heinze, T. (2006). Mapping the evolution of Nano S & T: Analytical and empirical tools. Workshop on mapping the emergence of nanotechnologies and understanding the engine of growth and development, March 1–3, 2006, Grenoble, France.

Heinze, T., Shapira, P., Senker, J., & Kuhlmann, S. (2007). Identifying creative research accomplishments: Methodology and results for nanotechnology and human genetics. *Scientometrics*, *70*(1), 125–152.

Hollanders, H. (2007). *2006 European Regional Innovation Scoreboard (2006 RIS)*. Maastricht, The Netherlands: Maastricht Economic Research Institute of Innovation and Technology.

Lerner, J. (1999). The government as venture capitalist: The long-run impact of the SBIR program. *The Journal of Business*, *72*(3), 285–318.

Mangematin, V. (2006). Emergence of science districts and divergent technology: The case of nanotechnologies. Mapping the emergence of nanotechnologies and understanding the engine of growth and development, March 1–3, 2006, Grenoble, France.

Morgan, K. (1997). The learning region: Institutions, innovation and regional renewal. *Regional Studies, 31*(5), 491–503.

Moulaert, F., & Sekia, F. (2003). Territorial innovation models: A critical survey. *Regional Studies, 37*(3), 289–302.

National Nanotechnology Advisory Panel. (2005). *The National nanotechnology initiative at five years*. Washington, DC: President's Council of Advisors on Science and Technology.

National Science Board. (2004). *Science and engineering indicators 2004*. Arlington, VA: National Science Foundation.

National Science Board. (2006). *Science and engineering indicators 2006*. Arlington, VA: National Science Foundation.

Noyons, E. C. M., Buter, R., Ran, A. F. J. V., Schmoch, U., Heinze, T., Hinze, S., & Rangow, R. (2003). *Mapping excellence in science and technology across Europe—Nanoscience and nanotechnology*. Report to the European Commission. Leiden, The Netherlands: University of Leiden.

OECD. (2006). *Main Science and Technology Indicators (MSTI)* (2006/2 ed.). Paris: Organisation for Economic Cooperation and Development.

Pennock, C., Doran, S., Youtie, J., Shapira, P., Bhaskarabhatla, A., Lamos, E., Malani, U., Slanina, J., Stephens, A., & Tang, L. (2006). *Connecting the dots: Creating a southern nanotechnology network*. Research Triangle Park, NC: Southern Technology Council, Southern Growth Policy Board.

Porter, M. E. (2000). Location, competition, and economic development: Local clusters in a global economy. *Economic Development Quarterly, 14*(1), 15–34.

Porter, A. L., Youtie, J., Shapira, P., & Schoeneck, D. (2007). Refining search terms for nanotechnology. *Journal of Nanoparticle Research*, forthcoming.

Powell, W., Koput, K., Bowie, J., & Smith-Doerr, L. (2002). The spatial clustering of science and capital: Accounting for biotech firm-venture capital. *Regional Studies, 36*(3), 291–305.

Project on Emerging Nanotechnologies. (2007). *Nanotechnology now used in nearly 500 everyday products*. Washington, DC: Woodrow Wilson International Center for Scholars. May 15.

Roco, M. C. (2004). Nanoscale science and engineering: Unifying and transforming tools, *AIChE Journal*, *50*(5), 890–897.

Rosenfeld, S. (1992). *Competitive manufacturing: New strategies for regional development*. New Brunswick, NJ: CUPR Press.

Shapira, P. (2005). Innovation challenges and strategies in catch-up regions. In G. Fuchs & P. Shapira (Eds.), *Rethinking regional innovation and change: Path dependency or regional breakthrough?* (pp. 195–222). New York: Springer.

World Economic Forum. (2006). *Global competitiveness report, 2006–2007*. Geneva: World Economic Forum.

Youtie, J., Iacopetta, M., & Graham, S. (2007). Assessing the nature of nanotechnology: Can we uncover an emerging general purpose technology? *Journal of Technology Transfer*, forthcoming.

Zucker, L., & Darby, M. (2005). Socio-economic impact of nanoscale science: Initial results and NanoBank. NBER Working Paper No. W11181, Cambridge, MA.

Zucker, L., Darby, M., & Brewer, M. (1998). Intellectual human capital and the birth of U.S. biotechnology enterprises. *The American Economic Review, 81*(1), 290–306.

Footnotes

[1] Membership of the Southern Growth Policies Board (SGPB) comprises the 13 US states of Alabama, Arkansas, Georgia, Kentucky, Louisiana, Mississippi, Missouri, North

Carolina, Oklahoma, South Carolina, Tennessee, Virginia, and West Virginia (plus the Commonwealth of Puerto Rico, which is not included in the analysis in this paper). Population estimates from US Census Bureau data for state resident population in 2005. We refer to the 13 states as the Southern Growth (or Southern) region.

[2] The CREA nanotechnology search strategy was based on earlier definitional work undertaken by the Centre for Science and Technology Studies at Leiden University and the Fraunhofer Institute for Systems and Innovations Research (see Noyons et al. *2003*).

[3] The nomination process involved input from 140 nanotechnology experts in the US and Europe surveyed in 2005 by the CREA project (see Heinze et al. *2007*).

[4] The specific search term we used was: nano* AND NOT (nanomet* OR nano2 OR nano3 OR nano4 OR nano5 OR nanosecon* OR (nano secon*)). The search was made in September 2005.