***D R A F T: SUBJECT TO REVISION – COMMENTS WELCOME***

# Prototypes of emerging metropolitan nanodistricts in the United States and Europe

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## Abstract

In this paper, we probe nanotechnology research and commercialization at a regional level. The study identifies leading US and European prototype “nanodistricts” or metropolitan areas active in nanotechnology research over the 1990-2006 timeframe. We explore the factors underlying the emergence of these metropolitan areas through exploratory cluster analysis. We find that while most of the leading nanodistricts are found in locations that were prominent in previous rounds of emerging technologies, new geographic concentrations of nanotechnology research have also surfaced.

Keywords: Nanotechnology, NanoIndicators, Regional Clusters

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## 1. Introduction.

Nanotechnology, which involves manipulating molecular-sized materials to create new products and process with novel features due to nanoscale properties, is widely anticipated as one of the next drivers of technology-based business and economic growth (Lux Research, 2006). It has been suggested that nanotechnology is a general purpose technology with potentially broad implications in redefining products, industries, and skills (Youtie et al., 2007). However, although the economic and societal effects of the application of nanotechnology are likely to be widespread, this does not mean that the benefits (and also the risks) will be distributed evenly (see, for example, Invernizzi et al., 2007).

In this paper, we focus on one aspect of the distributional implications of nanotechnology – namely, the distribution of nanotechnology development at the regional location level. The dynamic regional clusters of research institutions and firms where nanotechnologies are emerging have been denoted as "nanodistricts" (Mangematin, et al., 2005). Nanotechnology *applications* – be they in industrial products, consumer goods, medicine, or the environmental and energy sectors – will surely be deployed widely over time and space. But we may expect a smaller number of nanodistrict locations to appear where nanotechnology *research, development and initial commercialization* are clustered together. Support for this proposition can be found in studies of prior rounds of new technology development in the US, for example in microelectronics (Saxenian, 1994) and biotechnology (Cortright and Meyer, 2002). In these respective fields, just a handful of US cities have materialized as first-tier leaders, followed by a larger group of second-tier locations which are smaller in scale, often more specialized, and less dynamic in private-sector innovation even though R&D itself can be strong.

Probing where new nanotechnology districts will emerge is important for several reasons. Policymakers in many countries are investing significant amounts of R&D funding into nanotechnology domains, including in the US (where the multi-agency National Nanotechnology Initiative has annual budget of about $1.5 billion), as well as in Europe, Japan and China (Lux Research, 2006). Among other objectives, these policymakers anticipate that their nanotechnology R&D investments will lead to commercialization and new nanotechnology enterprise development. Regional policymakers (including in at least 30 US states) are providing additional funds and policy support for nanotechnology centers and programs within their jurisdictions. From both national and regional policy perspectives, it is helpful to benchmark where and how new regional nanodistricts are developing (as well as where they are not) and to feed such insights back into the policy development process. Moreover, and perhaps more subtly, there is an argument that the characteristics of a region influence the ways in which a new technology develops and is commercialized. For instance, Saxenian (1994) observes that the flat corporate structures and flexible innovation culture found in Northern California's Silicon Valley stimulated a decentralized and open approach to microcomputer development that proved to be successful in the marketplace. If this observation holds true for other fields, then knowing the characteristics of the leading regional nanodistricts (which first requires identifying where those districts are) could be helpful in the anticipatory governance of nanotechnology (Fisher et al, 2008) and the development of policies to ensure that nanotechnology meets desired societal goals. In short, the spatial distribution of locations for new technology has implications for the concentration of future business and economic opportunities. It may also influence the nature of commercialization and the management of risks for new technology development.

In exploring where nanotechnology development is taking place – and how it is occurring –we need to keep in mind that the cycle for nanotechnology emergence is still at an early stage. Four generations of nanotechnology development have been posited by Roco (2004) over the next two decades – passive nanostructures (including aerosols, coatings), active nanostructures (including targeted drugs, adaptive structures), systems of nanosystems (including guided assembly), and molecular nanosystems (including molecular nanosystems). At present, nanotechnology development is still mostly in the first generation. Hence, while more than 600 nanotechnology-based consumer products are already in the marketplace (Project on Emerging Technologies, 2008), these are primarily “nano-enabled” products where companies have made incremental improvements to existing products (for example, by using sub-100 nanometer semiconductor chips or introducing nanoparticles into creams and cleaning liquids to claims of enhanced performance). As yet, nanotechnology devices or systems with fundamentally different functions and properties have been envisioned but are nowhere near commercialization. There has been a noticeable growth in nanotechnology patenting (Huang, et al., 2003; Porter et al., 2007), as well as growth in new nanotechnology startup enterprises with over 230 such ventures identified in the U.S. (Wang, 2008). Nonetheless, at this point, most activity in nanotechnology remains at the phase of research and development, both in public institutions and private companies.

Additionally, we need to note the multi-disciplinary and multi-sectoral nature of nanotechnology. The domain of nanotechnology encompasses multiple knowledge fields, including those of engineering, biology, chemistry, materials science and computing (Rocco and Bainbridge, 2003; Nordmann, 2004). The applications of nanotechnology are also diverse, ranging from uses in resource and materials industries, consumer products, electronics, energy, environmental control, medicine, and aerospace, with many opportunities for convergence such as in nano-biotechnology or nano-medicine. Indeed, corporate publications and patents in nanotechnology are found not only spread over a large number of fields, but are also undertaken by firms both of large and small size (Avenel, 2007). Thus, comparisons can and should be made with innovative regional clusters that have developed in prior rounds of technological development (such as in electronics and biotechnology), and it is likely that there will be relationships and path-dependencies between these existing innovation clusters and the formation of nanodistricts. Yet, given the diversity of nanotechnology, it is plausible to expect that nanodistricts will also appear in new locations. Moreover, new nanodistricts might involve a wider range of industries and firm types (e.g. incumbents and new entrants as well as large and small firms) than seen in prior rounds of technology development (Bozeman, et al., 2007).

Of course, it is still premature in the cycle of development of nanotechnology to fully confirm where all nanodistricts will appear and how they will be constructed. However, we propose that we can identify *prototypes* of emerging nanodistricts. It is possible to make out locations at the sub-national level where nanotechnology R&D activity is concentrating – this is important, since nanotechnology depends upon research infrastructure and equipment, scientific and technical human capital resources, the creation and acquisition of knowledge, and the development of tools and techniques which can understand and manipulate materials, devices and systems at the molecular scale. If we able to characterize this R&D (for example, by scale and scope, sub-fields, organizational actors, collaborative relationships) and relate this to characteristics of innovation, we should be able not only to discover where likely nanodistricts are developing, but also understand sufficient characteristics of those areas to classify them. This will help us to understand the spatial distribution of nanotechnology clusters, including whether they are tightly concentrated (as in biotechnology) or more broadly distributed. Such analysis will also shed light on questions about the diversity of nanodistrict formation and possible trajectories of their future development.

## 2. Conceptualizing Nanodistrict Formation

In an earlier paper, which explored the emergence of nanotechnology clusters at the metropolitan level in the US, we discussed a series of concepts useful in characterizing prototypical nanodistricts, drawing on insights from the literature on new technologies and regional development (Shapira and Youtie, 2008). That paper reviewed the debate about unevenness, path dependency in regional technology development (Fuchs and Shapira, 2005) and considered its extension to questions about whether areas are able to leverage their capabilities in prior rounds into an early entry into nanotechnology. (Zucker and Darby 2007). However, fresh rounds of technology development invariably offer hope not only for new places to develop but also to combine locational and technological characteristics to pursue innovative applications and strategies. If nanotechnology is a general purpose technology with wide impacts across the economy (Youtie et al, 2007) then there may be the potential for new geographic concentrations of nanotechnology research, eventual applications, and risks. One factor in the spread of nanotechnology R&D into new regions might be investment in organizational capabilities. A region may invest in large research facilities such as particle scattering facilities, specialized clean rooms, and nanotechnology scoping and lithography equipment (Mangematin 2006). Alternatively, a region may focus its investments on a key “anchor tenant” – typically a university – by supporting the construction of new facilities or support for academic faculty to construct a center of excellence (Agrawal and Cochburn 2003). Then again, a region may seek to develop multiple organizational nodes of nanotechnology research activity, hoping that exchange and diversity among these organizations will foster new knowledge breakthroughs and innovative combinations (Shapira, et al., 2003).

Another avenue that a region aspiring to become a nanodistrict may take is to focus strategies on the development of human capital. Regions may seek to attract star scientists (Zucker et al, 1998) hoping that these scientists will spin-off startup firms and serve as a magnet for the location of R&D facilities or other outposts of larger more established firms. A further form of human capital investment involves the creation of networks of nanotechnology researchers. These networks may be intra-regional to link up and foster collaboration among scholars in different departments within a university or at different universities in the same city. Or the networks may be external to the region – at national and international levels – establishing connections between nano scholars in leading global universities with those in regions with aspirations to succeed in nanotechnology but with less of a technology tradition (Bozeman and Rogers, 2002; Davenport and Daellenbach, 2006; Kay and Shapira 2008).

These concepts offer us a set of propositions about the development and characteristics of prototypical nanodistricts. Thus, the possibilities are that nanotechnology will develop in locations that (1) are current leaders in high-technology innovation, building on their well-established stocks and flows of dynamic capabilities; (2) possess the organizational capital and resources associated with large-scale public or private research facilities; (3) develop or attract high-levels of scientific and technical human talent or star scientists; or (4) materialize as hubs in inter-regional networks of knowledge exchange and fusion in nanotechnology domains. Importantly, these prototypes are not mutually exclusive – some or all may develop simultaneously. Other variations and combinations may also emerge. Additionally, we do not presume that each of these different types will follow the same developmental trajectory or converge to produce similar outcomes and impacts. However, we do suggest that this set of propositions about the ways and means through which nanodistricts may develop does at least offer us a starting framework for inquiry.

The aim of this research is to empirically investigate the characteristics of prototype nanodistricts in selected leading developed economies and their regional distribution. We probe whether the economic distribution of nanotechnology will be geographically similar to that of past technologies or if new geographic clusters of nanotechnology activity will appear. Additionally, we also use the evidence gathered to conjecture about the possible trajectories of these prototypical nanodistricts – to contemplate the interrelationships between the foundations of the district and expectations about the prospective nature of innovation.

We explore these question in comparative perspective by investigating the development of nanodistricts in the US and Europe. In both the US and in Europe, there have been major public investments in nanotechnology research, there are well-developed science and innovation infrastructures, and each has deep pools of human capital, numerous large and small companies active in technology-oriented development, and innovative regional clusters. The US and Europe lead the global nanotechnology research enterprise in terms of publication quantity and quality, as measured by citation counts (Youtie et al., 2008). Yet there are also differences between the US and the multiple countries of Europe in terms of governance, research frameworks and funding, organizational landscapes, and even public attitudes towards nanotechnology (Kuhlmann and Shapira, 2006; Scheufele and Brossard, 2008). Exploring the development of nanodistricts in both the US and Europe allows us to validate and learn through comparison, as well as offering landscapes to explore leading to variations in the types of nanodistricts that may appear.

The next section presents our data and methods. This is followed by a consideration of results and discussion of implications.

## 3. Data and Methods

In this section, we discuss our approach to exploring the development of prototypical nanodistricts in the US and Europe. In particular, we explain how we operationalize the concept of the nanodistrict. We then describe the empirical measures and indicators used to test theories and propositions about factors that influence the spatial development of new nanotechnologies.

As noted earlier, the nanodistrict concept designates a regional area where research institutions and firms active in developing nanotechnologies are located. Although there are different levels of spatial delineation that could be applied to this concept (including the level of the state, province, or city), we judge that the metropolitan level is the most apt level. Metropolitan areas usually comprise several neighboring cities, often with a major core city, that function as an agglomerated unit in terms of labor market and commuting flows, transportation, local access to universities, research institutions, financial resources, and business support services, and localized knowledge exchange and spillover. (For discussions of the importance of metropolitan areas in high-technology research and innovation, see Harrison et al., 1996; Feldman and Audretsch, 1999; Acs, 2002.) We thus use the metropolitan area as the level of aggregation for searching for nanotechnology emergence.

As the key measure in identifying metropolitan areas prominent in nanotechnology, we use the performance of institutions and corporations in that area in nanotechnology publication.[1]

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[1] The science-driven nature of nanotechnology development justifies the use of research publication output as a filter. While most research publications are produced by universities and research institutions, business organizations also produce publications (for example, in the US, about 11 percent of all nanotechnology publications in the period 1990 through mid-2006 had a corporate author or co-author). Hence, while businesses do not publish

Data are derived using a multi-stage Boolean search strategy for identifying research publications in the nanotechnology domain.[2] This provides a global database of more than 400,000 publication records (for the period 1990 through mid-2006) downloaded from the Science Citation Index of the Web of Science. All authors in the publication record are mapped into a city and state according to the geographic location of the institutions – university, government laboratory, corporation, etc. – with which the authors are affiliated. These are then aggregated to the combined statistical area where this designation is available, or otherwise to the metropolitan area. (OMB 2006). For example, we designate the Washington DC-Baltimore combined statistical area as our unit of analysis rather than treating the two as separate metropolitan areas. But in the case is Madison Wisconsin, we use the metropolitan area as our unit of analysis because this area is not part of a combined statistical area.

Analysis of European metropolitan nanotechnology research publication output is more challenging because there is no standard European definition of a metropolitan area.[3] Each country has its own definition and, in some countries, there is no official definition of a metropolitan area. As a starting point, we used the Nomenclature of Territorial Units for Statistics (NUTS) classification (which covers the European Union). We focused on the fine-level NUTS 3 unit, of which nearly 1100 have been defined among the 27 members countries of

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all they know, they do make some efforts at publishing or making conference presentations which can be interpreted as one of the signals of business entry into the nanotechnology field. An alternate measure would be to look at patenting. However, once we overcome some technical issues related to geographical allocation of European patenting, we seek (in an extension of this research) to use patenting to further measure the level of innovative activity in nanodistricts in the US and Europe. We have already undertaken analysis of the role of patenting in US nanodistricts (Shapira and Youtie, 2008).

[2] The Georgia Tech nanotechnology datasets include more than 400,000 global nanotechnology records in the Web of Science's Science Citation Index (WOS-SCI) for the period 1990-2006 (mid year) and nearly 54,000 global nanotechnology-related abstracts of patents awarded in this same timeframe reported from the MicroPatents database. The methodology used to develop these datasets is discussed in Alan L. Porter, Jan Youtie, Philip Shapira and David J. Schoeneck, Refining search terms for nanotechnology, *Journal of Nanoparticle Research* (published online 2007 at DOI 10.1007/s11051-007-9266-y; print publication forthcoming).

[3] The definition of Europe used in searching for metropolitan nanodistricts comprises *continental* Europe, including the 27 member states of the European Union, Switzerland, Norway, Russia (west of the Urals), and the Ukraine.

the European Union (EU). NUTS 3 regions were aggregated together as in the OECD Competitive Cities Report (2007). We then checked these regions for coherence drawing buffers of various sizes between the two farthest cities in these regions; these areas ranged from 11 miles (17.7 km) (Prague) to 59 miles (95 km) (Cologne) with a mean of 37 miles (59.5 km) and a standard deviation of 11 miles (17.7 km). Very big regions were modified to exclude certain geographic areas that lacked coherence. This method was used to define 20 metropolitan areas with high levels of nanotechnology research output in Europe. A single NUTS 3 region was used to designate another 11 metropolitan areas. Regions in Russia, Ukraine and other parts of Eastern Europe lacked NUTS classifications, so we used simple searches of cities to delineate four more metropolitan areas (See Table 1).

These methods yielded 30 US metropolitan areas with more than 1000 nano-related publications and 35 European metropolitan areas with more than 1400 nano-related publications (1990 through mid-2006). The publication threshold level is based on judgment (the level could be set higher or lower). However, we sought a group of sufficient size with less heterogeneity than if we were to include the total population of all metropolitan areas with authors publishing on nanotechnology. Also we note that it is very time consuming to organize this data, particularly to code it geographically. For example, the top 30 metropolitan areas in the US accounted for nearly 90,000 nanotechnology publication records from 1990 to 2006, so the databases are quite large.

The final set of identified metropolitan areas for the US and Europe is listed in Table 2 and presented as maps in Figures 1 and 2. The circles in the maps are situated at the centroid of the metropolis and their size is proportionately scaled to the total number of locally-authored publications. The US map shows concentrations in recognized technology-leading regions –

California and the Northeast – but also in the rustbelt and sunbelt. Likewise the European map shows concentrations in expected locations in Western Europe but there is also representation in Russia, the Ukraine, and some parts of Eastern Europe.[4]

The next step in our method is to categorize these metropolitan areas active in nanotechnology research into prototypical nanodistricts. Drawing on the concepts of nanodistrict formation discussed in the previous section, we identified specific empirical measures that plausibly could be applied to test for the presence or level of a particular factor posited as important in the development of different types of nanodistricts. Table 3 lists these measures, relates them to conceptual factors identified in the literature, and presents summary descriptive statistics. Hence, concepts of path dependency – which suggest that nanodistricts will emerge in regions that already have strength gained through prior and current rounds of technological development – are proxied by absolute publication counts, the percentage of publications in the early 1990-1995 time period (to measure early-mover advantage), and the percentage of publications involved in nanobiotechnology. The latter measure is included to represent the proposition that nanotechnology's regional distribution may be similar to biotechnology – a prior emerging technology. Human capital factors relating to (1) eminent scientists are proxied by highly cited publications or the percentage of publications since 2000 with 25 or more citations, and (2) research networks are proxied by levels of coauthorship – the number of authors per article and the percentage of articles co-authored with authors who are based outside the metropolitan area of interest. Organizational capital factors include (1) the facilities-based approach, which is proxied by the percentage of publications with an author from a government laboratory or a private non-profit research institute that serves a comparable role, and (2) the

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[4] The authors have produced an animated visualization of nano publication growth, by year, of US nanodistricts, 1990-2006. This is available at http://www.nanopolicy.gatech.edu/maps.htm.

relationship between an dominant anchor tenant versus organizational diversity in a region, which is represented by a Herfindahl Index that measures the institutional concentration (or dispersion) of publications in a given metropolis.

An examination of mean differences in these nanodistrict characteristics indicated that there were significant differences between metropolitan areas in the US and in Europe along many of these characteristics. Caution needs to be exercised in interpreting these differences, because definitional or technical factors may have an influence. For example, in measuring institutional diversity, there are standardized lists of universities and government laboratories for the US but it is hard to find similar standardized lists for the 35 European nanodistricts, so the higher institutional diversity measures for Europe may be a reflection of data cleaning issues. On the other hand, the percentage of highly cited publications, percentage of nanobio publications, and early time-period publications – significantly higher on average for US publications than European publications – are less subject to data errors and more representative of continental differences. In any case, we must treat these as separate population groups for further analysis.

We characterized our nanodistricts by classifying them based on the aforementioned attributes using hierarchical cluster analysis based on Ward’s method using Euclidean squared distances and standardizing the nanodistrict attributes so they would receive equal weight in the analysis. After experimenting with multiple solutions using the US subset of the data, we settled on a 7-cluster solution as giving us sufficient variation while still being rather parsimonious in its representation of the data (Shapira and Youtie 2008). We then applied a comparable 7-cluster solution to the European nanodistricts. The resulting dendogram looks similar to the one for the US except that it bifurcates into two groups in a more dramatic fashion.

## 4. Results

Tables 4 shows the membership of the top US and European nanodistricts in the clusters under analysis. We interpreted the attributes of these clusters, and assigned names based on this interpretation, using the data in Table 5. The results of the cluster analysis indicate many areas of similarity as well as important differences between the US and Europe. Both countries/blocs have *technology leaders* (TLEAD). These are metropolitan areas that have commonly appeared at the top of lists of biotechnology and other prior rounds of emerging technologies, including the Bay area in Northern California (which includes Silicon Valley), Boston, Washington DC, and Chicago in the US and Paris, London, Frankfurt, Berlin, and the Rhine-Ruhr (Cologne) in Europe. TLEAD areas have among the highest number of publications and a relatively high proportion of publications in the early 1990-1995 time period, and a somewhat higher percentage of recent year highly cited publications.

We also have two clusters of metropolitan areas where the nanotechnology publication base is dominated by a particular type of organization. *University-led areas* (UNIV) have more than 95 percent of their publications authored by researchers in academia. While the average number of publications in a UNIV nanodistrict is on the lower side of the leading metropolitan areas, UNIV represent some of the leading universities in the US and Europe, including Oxford and Cambridge in Europe and Ithaca (Cornell), Lafayette (Purdue), and Champaign-Urbana (University of Illinois) in the US. These cities are the most self-contained in that they have a relatively low percentage of publications authors by researchers outside of the UNIV nanodistricts, and also lower author to article ratios. UNIV nanodistricts in the US also have the highest percentage of publications authored in the early time period. UNIV nanodistricts in Europe also have relatively higher percentage of early publications.

Areas led by *government laboratories* (GOV) comprise three US nanodistricts and six European nanodistricts. The GOV cluster is more important and includes more nanodistricts in Europe in part because of the number and diversity of public or quasi-public facilities including government-funded laboratories such as the Crolles 2 facility in Grenoble (France), but also well-established nonprofit organizations that undertake research, such as the Fraunhofer Society in Germany. Although GOV facilities in general are not at the very top of these 65 nanodistricts in terms of publications, they typically have higher organizational diversity often in partnership with a local university. They also are engaged in more co-authorships and more externally-located authors, suggesting an important networking role that associates hard facilities investments with soft networking relationships.

The cluster analysis identifies one *geographically-focused cluster* in the US and one in Europe (GEOG). The GEOG-US cluster is centered in Southern California (comprising the metropolitan areas of Los Angeles and San Diego). This cluster has the highest percentage of recent publications with 25 or more citations, which is in keeping with the work of Zucker et al. (1998) on star scientists in biotechnology (both San Diego and Los Angeles are strong in nano-biotechnology). This cluster also has a relatively high level of corporate publication activity. We also identify a geographically-focused cluster, GEOG-EUR, set in Eastern Europe (including Russia). The European geographical cluster comprises five nanodistricts in Eastern Europe: Moscow, St. Petersburg, Kiev, Warsaw, and Prague. Moscow has the second highest number of publications among all 35 European nanodistricts. The Eastern European cluster is also characterized by a high percentage of publications authored by university scientists, just above the average for UNIV nanodistricts in Europe, a low rate of highly-cited articles, and a very low level of corporate nanotechnology research authorship.

The cluster analysis had two groups of nanodistricts that were less distinguishable than were the aforementioned areas, which we call DIV and LENT. DIV is comprised of eight *midrange diverse* nanodistricts each in the US and Europe that have below average counts of publications (among the leading nanodistricts). However, these metropolitan areas have higher percentages of nanobio activity. This group includes such metropolitan areas as Philadelphia in the US and Munich in Germany. They are also have more institutionally diverse research actors, with lower Herfindahl Index scores, and have relatively higher percentages of corporate-authored publications. LENT comprises *midrange late-entry* nanodistricts, of which there are eight in the US and four in Europe. This group includes locations such as Atlanta in the US and Strasbourg in France, where individual institutions (such as Atlanta's Georgia Tech or Strasbourg's University Louis Pasteur/CNRS) have began to accumulate nanotechnology research momentum in recent years.  While they have among the lowest number of publications, they also have the highest percentage of later publications since 2001-2006. There is less institutional diversity in these nanodistricts and a strong university presence, particularly for the eight US LENT areas, and a relatively lower corporate share in research output. Highly cited works account for a slightly higher percentage of publications among LENT nanodistricts in Europe.

There is one cluster respectively in the US and in Europe that was an outlier or *one-off model* in the hierarchical analysis. In the US, New York had the highest number of publications and a significantly higher percentage of corporate-affiliated authors. Indeed, New York is particularly distinctive for the large role that corporations play in nanotechnology research outputs (it is home to IBM and other major corporate research facilities). In Europe, Madrid also had a high total number of publications – in the top 10 European nanodistricts – and had a 50-50 mix of publications from universities and government laboratories. However, unlike New York, Madrid has low-level of corporate research authorship in nanotechnology and a relatively lower level of co-authorship collaboration with researchers outside of Madrid.

We emphasize that this cluster analysis identifies prototypical nanodistricts – and, of course, further work is needed to analyze their characteristics in more detail, including their propensity to initiate nanotechnology innovations (for example, through patenting), new nanotechnology business formations, licenses, and industry partnerships with universities and laboratories. However, there are hints as to what we might expect to find in terms of nanotechnology innovation and business engagement, as well as to the spatial distribution of different types of nanotechnology district development. Looking at the engagement of business, relatively high levels of corporate nanotechnology activity are found in the technoleaders (Bay Area, Boston, Washington DC-Baltimore, Chicago, Paris, London, Frankfurt, Berlin and the Rhine Ruhr) and in New York. These metropolitan regions, which draw on significant previously-established and diverse research, human capital, financial, and reputational assets, look well-position to emerge as leaders in nanotechnology innovation. There is a second-tier group of mid-range diverse metropolitan areas in the US (9) and Europe (7) which also have relatively good corporate levels of activity and from which several may emerge as significant locations for nanotechnology innovation. Both in the US and in Europe, there is a set of active nanotechnology research locations – including university and government-lab dominated cities – where single institutions dominate and corporate publication activity is lower. We would anticipate that in these locations, especially in university cities (such as Santa Barbara, Oxford, or Cambridge) or cities where universities dominate nanotechnology research (such as Manchester), there will be start-up activity and the formation of new nanotechnology enterprises. This is probably also a reasonable expectation for the Southern California (SOCAL) nano-biotechnology cluster.  However, at the other end of the scale, metropolitan areas such as Madrid or Moscow, which are large producers of nanotechnology publications but which lack corporate activity may find it more difficult to translate their research output into private-sector commercialized applications within in their region (some of these outputs may be applied elsewhere).

## 5. Conclusions

This analysis has shown that publications can be aggregated at the metropolitan area to produce nanodistricts. One limitation is the lack of a standard definition of metropolitan areas in Europe. In addition, while we would also wish to present data on patenting, our database of nanotechnology-related patents does not have geographic locations of inventors for the various in-country patent offices (although we have this for the European Patent Office and for the World Intellectual Property Organization) whereas we do have this type of information fully represented in the US Patent and Trade Office segment of the database. In the future, being able to compare the link between publication characteristics and commercialization, represented by patenting, would be an important area of analysis.

For both the US and the EU, we find that there is strong evidence of path dependency. The same (TLEAD, GEOG-US) cities that are in leading positions in prior rounds of technology, especially in biotechnology, are (for the US metropolises) also in the lead in terms of number of patents in nanotechnology (see Shapira and Youtie, 2008). The authors located in these districts were early researchers into the field of nanotechnology, which further enabled their ability to maintain a leading position. They also had a diversity of institutional participants including corporate publication activity. Moreover, they have a relatively higher percentage of publications in nano-biotechnology.[5]

While we found that path dependency was prominent in nanotechnology, we also found that there were some new geographical areas that were not in a leading position in biotechnology or other prior technologies. These nanodistrict prototypes can be found in GOV, UNIV, LENT, and DIV clusters. The importance of anchoring publication activity around a single university or an investment in government facilities played a major role in moving the nanodistricts in these clusters into their current position.

On the whole, we found that organizational strategies were most important in distinguishing nanodistricts. That is not to say that human capital investments are unimportant. Rather almost all the nanodistricts in this study have similar levels of highly cited research and relationships with authors outside of the metropolitan area. However, organizational strategies were more diverse among those nanodistricts with the very highest number of publications, whereas they were more monocentric in the GOV, UNIV, and LENT regions. It could be concluded that monocentric organizational approaches work well for nontraditional technology regions in the near-term. However, broadening and strengthening organizational capital (as well as human capital) and ties to commercial applications and demand will be important in the long-term.

What lessons can US nanodistricts learn from those in Europe and vice versa? The US can learn from the diversity and strength of government laboratories and the links of these laboratories to other organizational participants, including corporations. For example, the

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[5] One might suggest that this biotechnology relationship might stem from an overly broad definition of nanotechnology that includes too much biotechnology. This was a concern of Porter et al (2007) as we developed the initial database. A panel of 19 nanoscientists was surveyed to guide the bibliometric definition used herein. One result was the use of terms such as DNA and RNA to delineate our definition of nanotechnology from that of biotechnology.

Crolles2 facility in Grenoble has alliances with multiple large and strong high tech companies including STMicroelectronics, Philips and Freescale. Oak Ridge National Laboratory also has excellent user facilities and some corporate participation, but not to the level of the Grenoble laboratory. In addition, Europe has a diversity of important private non-profit organizations that serve in a public-like laboratory role, which the US does not have. In contrast, US nanodistricts offer European nanodistricts lessons in greater importance of corporate-generated research, highly involved universities, and highly cited research.

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Table 1. Basis for European “Metropolitan Area” Definition

| Region | Country | Definition* | Radius miles (Central to Farthest city) | Large City | City with Most Nano Pubs. |
|---|---|---|---|---|---|
| Barcelona | Spain | OECD | 39 | Barcelona | Barcelona |
| Barnsley, Doncaster, Rotherham | UK | NUTS3, UKE31 | | Barnsley | South Yorkshire |
| Bas-Rhin | Germany | NUTS3, FR421 | | Strasbourg | Strasbourg |
| Berlin | Germany | OECD | 55 | Berlin | Berlin |
| Brussels | Belgium | OECD | 25 | Brussels | Louvain |
| Cambridgeshire | UK | NUTS3, UKH12 | | Cambridge | Cambridge |
| Dresden (Kreisfreie Stadt) | Germany | NUTS3, DED21 | | Dresden | Dresden |
| Frankfurt | Germany | OECD | 60 | Frankfurt | Mainz |
| Hamburg | Germany | OECD | 45 | Hamburg | Hamburg |
| Hampshire-Avon | UK | NUTS3, UKJ31&32&33 | | Southampton | Bristol (Avon) |
| Haute-Garonne | France | NUTS3, FR623 | | Toulouse | Toulouse |
| Isère | France | NUTS3, FR714 | | Grenoble | Grenoble |
| Karlsruhe | Germany | NUTS3, DE122&DE123 | | Karlsruhe | Karlsruhe |
| Kiev | Ukraine | VP | | Kiev | Kiev |
| Lancashire | UK | NUTS3, UKD43 | | Manchester | Manchester |
| Lausanne | Switzerland | VP | | Lausanne | Lausanne |
| London | UK | OECD | 42 | London | London |
| Lyon | France | OECD | 19 | Lyon | Villeurbanne |
| Madrid | Spain | OECD | 36 | Madrid | Madrid |
| Milan | Italy | OECD | 49 | Milan | Milan |
| Moscow (& Region) | Russia | VP | | Moscow | Moscow |
| Munich | Germany | OECD | 47 | Munich | Munich |
| Oxfordshire | UK | NUTS3, UKJ14 | | Oxford | Oxford |
| Paris | France | OECD | 41 | Paris | Paris |
| Prague | Czech Republic | OECD | 11 | Prague | Prague |
| Randstad-Holland | Netherlands | OECD | 21 | Amsterdam | Leiden |
| Rhine-Ruhr | Germany | OECD | 59 | Cologne | Julich |
| Rome | Italy | OECD | 49 | Rome | Rome |
| St Petersburg | Russia | VP | | St Petersburg | St Petersburg |
| Stockholm | Sweden | OECD | 46 | Stockholm | Stockholm |
| Stuttgart | Germany | OECD | 37 | Stuttgart | Stuttgart |
| Västra Götalands Län | Sweden | NUTS3, SE0A2 | | Gothenburg | Gothenburg |
| Vienna | Austria | OECD | 24 | Vienna | Vienna |
| Warsaw | Poland | OECD | 27 | Warsaw | Warsaw |
| Zurich | Switzerland | OECD | 14 | Zurich | Zurich |

*OECD=definition of European cities in OECD (2007); NUTS 3= NUTS 3 classes used to define the area; VP=simple text-based search of the name of the city (in various forms) in the publication’s author affiliation field.

Source: Author’s analysis, drawing on OECD (2007).

Table 2. Number of Nanotechnology Publications in Top US and European Metropolitan Regions, 1990-2006 (mid)

| **US** | | **Europe** | |
|---|---|---|---|
| New York (NY) | 9612 | Paris | 8939 |
| San Francisco-San Jose (Bay Area) | 8717 | Moscow | 6417 |
| Boston | 7441 | Rhine-Ruhr | 6004 |
| Washington DC-Baltimore | 7073 | Berlin | 5715 |
| Los Angeles | 5414 | London | 5535 |
| Chicago | 4447 | Frankfurt | 4300 |
| Philadelphia | 3186 | Munich | 4151 |
| Research Triangle (NC) | 3112 | Madrid | 4073 |
| Champaign | 2977 | Grenoble | 3957 |
| Santa Barbara | 2646 | St Petersburg | 3800 |
| Detroit | 2434 | Randstad | 3129 |
| Houston | 2336 | Cambridge | 3015 |
| Atlanta | 2163 | Stuttgart | 2926 |
| Knoxville | 2154 | Hamburg | 2759 |
| State College | 1936 | Stockholm | 2449 |
| Cleveland | 1921 | Warsaw | 2416 |
| Minneapolis | 1903 | Lyon | 2388 |
| Austin | 1741 | Dresden | 2370 |
| Phoenix | 1736 | Brussels | 2349 |
| Albuquerque | 1683 | Rome | 2310 |
| San Diego | 1636 | Lausanne | 2280 |
| Pittsburgh | 1633 | Oxford | 2082 |
| Denver | 1606 | Zurich | 1970 |
| Ithaca | 1568 | Barcelona | 1950 |
| Gainesville | 1444 | Milan | 1897 |
| Madison | 1359 | Hampshire | 1789 |
| Seattle | 1314 | Strasbourg | 1736 |
| Lafayette | 1202 | Manchester (Lancs) | 1725 |
| Albany | 1163 | Toulouse | 1721 |
| Dallas | 1066 | Karlsruhe | 1680 |
| | | Kiev | 1654 |
| | | Gothenburg | 1611 |
| | | Prague | 1543 |
| | | Vienna | 1533 |
| | | S Yorkshire | 1463 |

Source: Author’s analysis, drawing on Georgia Tech nanotechnology global publication databases (see Porter et al., 2007).

Table 3. Operationalization of Nanodistrict Concepts: Comparison of US and European Publication Metrics and Differences

| Measures | Concept | US | | Europe | | |
|---|---|---|---|---|---|---|
| | | Mean | Stddev. | Mean | Stddev. | |
| **Total Publications** | **Path dependency** | 2954 | 2329 | 3018 | 1724 | |
| Pubs/mill. pop. | | 2893 | 4461 | 1502 | 1579 | * |
| **Herfindahl Index** | **Anchor tenant** | 0.46 | .29 | 0.26 | .19 | *** |
| **% Nanobio** | **Path dependency** | 11.5% | 4.8% | 9.5% | 4.8% | * |
| **% Government** | **Facilities** | 12.3% | 22.3% | 19.1% | 20.7% | |
| % University | Anchor tenant | 81.5% | 18.5% | 79.4% | 19.1% | |
| % Corporate | Anchor tenant | 12.1% | 7.8% | 6.4% | 5.3% | *** |
| **Early %** | **Path dependency** | 12.4% | 3.3% | 9.1% | 3.0% | *** |
| Late % | Path dependency | 60.9% | 5.2% | 60.7% | 4.6% | |
| **Authors/article** | **Network** | 2.04 | .36 | 2.12 | .40 | |
| % out-of-metro authors | Network | 50.9% | 10.1% | 61.9% | 10.8% | *** |
| **% highly cited pubs.** | **Stars** | 5.9% | 4.4% | 2.6% | 1.1% | *** |

Significance level: ***.01, **.05, *.10
Measure in bold were used to develop the 7-cluster solution.

Table 4. Nanodistrict Membership in Seven Clusters

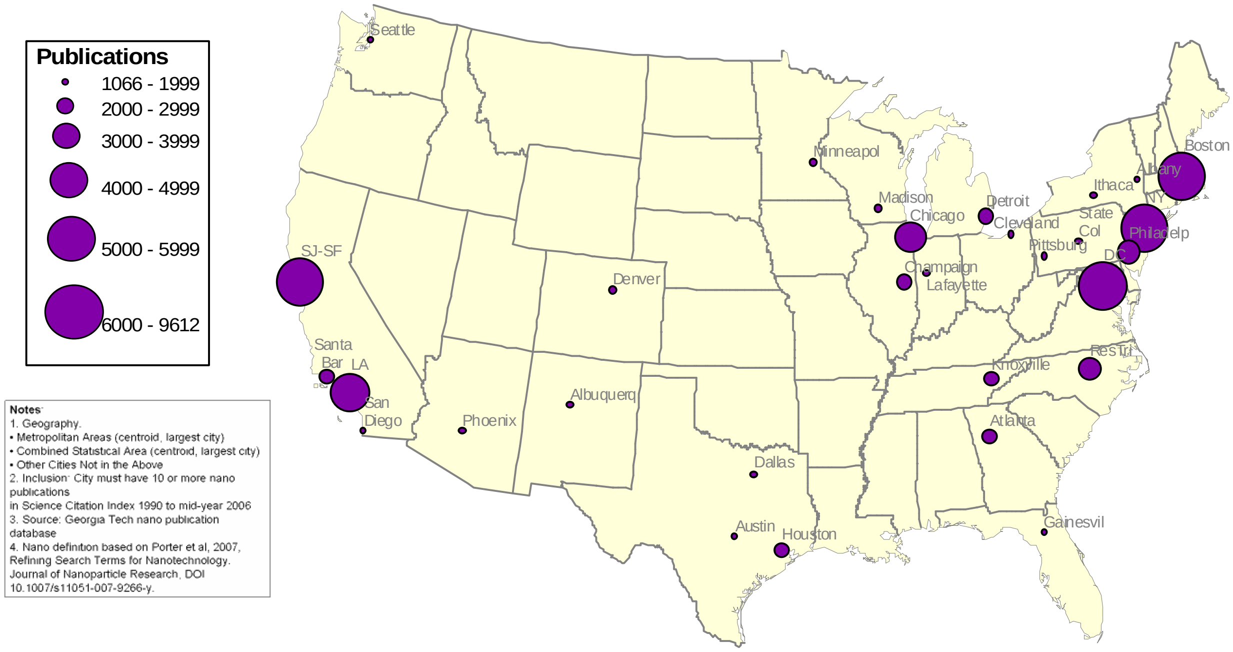
| **Cluster** | **US** | **Europe** |
|---|---|---|
| TLEAD | SF-SJ, Boston, DC-Balt, Chicago | Paris, London, Frankfurt, Berlin, Rhine-Ruhr (Cologne) |
| UNIV | Ithaca, Champaign, Santa Barbara, Purdue | Cambridge, Oxford, Gothenberg, Lancashire (Manchester), Lausanne, S. Yorkshire |
| GOV | Oak Ridge, Denver, Albuquerque | Grenoble, Stuttgart, Toulouse, Lyon, Milan, Rome |
| DIV | Cleveland, Dallas, Detroit, Houston, Minneapolis, Philadelphia, Pittsburgh, Research Triangle | Brussels, Hamburg, Munich, Randstadt, Stockholm, Vienna, Zurich |
| LENT | Albany, Atlanta, Austin, Gainesville, Madison, Phoenix, Seattle, State College | Barcelona, Dresden, Karlsruhe, Strasbourg |
| GEOG | Los Angeles, San Diego | Moscow, St. Petersburg, Kiev, Warsaw, Prague |
| ONEOFF | New York | Madrid |

Table 5. Attributes of 7-Cluster Solutions: US versus European Nanodistricts

| US | Middle Late LENT | Government GOV | Techno Leaders TLEAD | University UNIV | Middle Diverse DIV | S. Calif. Nanobio GEOG | New York ONEOFF | |
|---|---|---|---|---|---|---|---|---|
| Total Publications | 1607 | 1814 | 6920 | 2098 | 2199 | 3525 | 9612 | *** |
| Pubs. per mill. pop. | 3367 | 1734 | 912 | 10934 | 739 | 454 | 449 | *** |
| % Pubs. 1990-95 | 10.1% | 11.1% | 12.6% | 18.7% | 11.8% | 10.9% | 18.0% | *** |
| % Pubs. 2001-2006 | 64.7% | 59.7% | 60.4% | 53.0% | 62.8% | 59.8% | 54.6% | *** |
| % Nanobio | 10.0% | 5.1% | 14.3% | 8.0% | 14.1% | 16.6% | 13.8% | *** |
| % Gov. pubs. | 0.7% | 63.5% | 29.7% | 1.4% | 3.5% | 7.1% | 7.8% | *** |
| % Univ. pubs. | 92.7% | 43.6% | 67.4% | 98.2% | 86.2% | 81.1% | 58.3% | *** |
| % Corporate Publications | 10.5% | 8.2% | 14.5% | 4.0% | 15.1% | 11.8% | 36.6% | *** |
| Herfindahl Index | 0.70 | 0.39 | 0.17 | 0.86 | 0.32 | 0.19 | 0.05 | *** |
| Authors per article | 2.1 | 2.2 | 2.1 | 1.8 | 2.2 | 2.4 | 0.6 | *** |
| % articles not in district | 51.4% | 57.4% | 52.3% | 37.5% | 52.2% | 54.7% | 55.6% | |
| % articles with 25+ cites since 2000 | 5.1% | 3.2% | 5.9% | 4.3% | 4.7% | 21.2% | 5.0% | *** |
| # nanodistricts | 8 | 3 | 4 | 4 | 8 | 2 | 1 | |
| | | | | | | | | |
| EUROPE | LENT | GOV | TLEAD | UNIV | DIV | EE GEOG | Madrid ONEOFF | |
| Total Publications | 1934 | 2533 | 6099 | 2029 | 2516 | 3166 | 4073 | *** |
| Pubs. per mill. pop. | 2279 | 1436 | 743 | 3428 | 786 | 706 | 727 | ** |
| % Pubs. 1990-95 | 5.7% | 10.6% | 12.0% | 10.6% | 8.9% | 5.9% | 8.0% | *** |
| % Pubs. 2001-2006 | 66.1% | 60.2% | 57.1% | 57.0% | 61.2% | 64.3% | 62.3% | *** |
| % Nanobio | 6.8% | 7.9% | 12.3% | 8.5% | 14.8% | 3.6% | 7.3% | *** |
| % Gov. pubs. | 31.5% | 51.0% | 19.9% | 1.2% | 7.2% | 4.6% | 50.1% | *** |
| % Univ. pubs. | 72.6% | 53.3% | 69.2% | 95.1% | 89.5% | 96.3% | 54.1% | *** |
| % Corporate Publications | 5.5% | 4.9% | 13.5% | 4.9% | 7.7% | 2.2% | 2.5% | ** |
| Herfindahl Index | 0.20 | 0.14 | 0.07 | 0.58 | 0.22 | 0.30 | 0.23 | *** |
| Authors per article | 2.1 | 2.3 | 2.2 | 2.1 | 2.3 | 2.0 | 0.2 | *** |
| % articles not in district | 64.7% | 68.4% | 62.7% | 53.1% | 61.6% | 62.8% | 57.4% | |
| % articles with 25+ cites since 2000 | 3.6% | 2.0% | 2.8% | 2.9% | 3.5% | 0.9% | 2.1% | *** |
| # nanodistricts | 4 | 6 | 5 | 6 | 8 | 5 | 1 | |

Significance level: ***.01, **.05

Figure 1. Map of Location of Top US Nanodistricts by Number of Publications



**Notes**:
1. Geography.
- Metropolitan Areas (centroid, largest city)
- Combined Statistical Area (centroid, largest city)
- Other Cities Not in the Above

2. Inclusion: City must have 10 or more nano publications
in Science Citation Index 1990 to mid-year 2006
3. Source: Georgia Tech nano publication database
4. Nano definition based on Porter et al, 2007, Refining Search Terms for Nanotechnology. Journal of Nanoparticle Research, DOI 10.1007/s11051-007-9266-y.

Figure 2. Map of Location of Top European Nanodistricts by Number of Publications