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National innovation systems and the globalization of nanotechnology innovation

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Abstract While there has been much emphasis over the last decade on the science of nanotechnology and on the implications and risks of potential applications, it is now timely to increase attention to the emerging dynamics of nanotechnology commercialization. This paper examines, from a global perspective, where and how corporations are entering into nanotechnology innovation. The paper tests the proposition that a significant shift has occurred in recent years in the orientation of corporate nanotechnology activities—from research discovery to patented applications. It also examines the extent to which the character and structure of corporate nanotechnology activity by country initially reflects national innovation system characteristics and prior public research funding inputs in the stage when discovery is most emphasized. The results indicate that national innovation systems characteristics are significant factors in the commercialization shift of nanotechnology and highlight the importance of innovation system policy factors. We also observe the influence of cross-border international invention linkages, suggesting that national innovation policies also need to be open and international in orientation.

Keywords Nanotechnology · National innovation systems · Corporate research · Commercialization

JEL classification O3 · O5

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1 Introduction

Much has been written about strategies that companies use to enter new fields (Lieberman and Montgomery 1998). In general, firms enter markets when they perceive that their pre-entry resources and capabilities match the required resource profiles in those markets (Helfat and Lieberman 2002). First-mover advantages are likely to be highly industry-specific (VanderWerf and Mahon 1997), yet early entrants into new fields typically gain advantages in the ability to establish patents and trade secrets. This is especially important in recent science and technology intensive fields such as nanotechnology that are emerging during a period of high degrees of patenting (Mowery 2010). In addition, early entrants have the ability to control complementary assets, especially those complementary assets that are specialized, tied to nascent technologies, and expensive to acquire (Teece 1986). Ultimately, early entry can result in the appropriation of rents and spillovers into related businesses and localized regions, reinforcing and compounding the innovation advantages and systems of those businesses. There are also disadvantages to early entry, including technological uncertainty, higher costs of educating customers, free-rider abilities of other firms to learn from first mover positions, and the inability of first movers to respond quickly to changes in the market (Lieberman and Montgomery 1988). As a result of these problems, early entry has also been associated with high rates of failure, a situation not uncommon to small start-up businesses (Headd 2003). Indeed, a recent estimate of nanotechnology enterprises and jobs assumes that as many as 70 percent of nanotechnology firms wind up in mergers and acquisitions or go out of business.[1]

New perspectives have emerged on the role of internationalization versus national systems and markets in business entry. Conventional rhetoric proposed a stage model in which domestic activity is prioritized before entry into international markets takes place. National innovation systems are of particular prominence under this viewpoint in encouraging the creation of new high technology markets and firms. However, research over the last two decades has observed the growth of international venture development. (Oviatt and McDougall 1994; McDougall et al. 1994; Rennie 1993; Acedo and Jones 2007; Gilbert et al. 2006) Some new ventures, particularly those operating in small high technology markets, are born global because of opportunities to use international networks to reach a market of sufficient scale for supporting business entry. The internationality of these ventures occurs at inception largely because of competitive forces that preclude a successful domestic focus, suggesting strategies to manage rather than own assets such as unique knowledge (Oviatt and McDougall 2005). This perspective raises questions as to the extent to which the attributes of national innovation systems are still important in fostering new technology and market development or whether the rise of international entry reduces their relevance.

One key to understanding early entry (and perhaps to offering an edge in competitive innovation strategy) is to identify the timing and current stage of transition of a new field. It has been argued that nanotechnology is an emerging domain of new knowledge production that may be transitioning into a new wave of commercial interest. Lux Research (2007) maintains that nanotechnology is undergoing a shift from discovery to innovation, with increased emphasis on products, venture capital and equity finance, and rising quality of basic nanomaterials as a platform for enhancement of existing products and development of new products (Youtie et al. 2007). This perspective on nanotechnology's transition

[1] Chris Newfield (Center for Nanotechnology in Society, UC Santa Barbara), Internal correspondence, January 18, 2010.

incorporates an assumption of an accelerating growth curve as nanotechnology moves from research to commercialization. In contrast to this view of a linear or growth curve sequence, Schmoch (2007) observes that many science-based discoveries undergo two waves of growth, the first being propelled by research discoveries, followed by a stagnation phase in which discoveries are absorbed, followed by a second period of commercial oriented growth (Schmoch 2007).

However, it is not straightforward to discern the current stage of nanotechnology. The cumulative federal investment in nanotechnology in the US since 2001 is about $12 billion, most of which is for basic research. Companies are also investing in R&D, estimated at $2 billion a year in the US, which is marginally more than annualized government R&D, although presumably somewhat more downstream. Most available applications are still in the early passive phases of nanotechnology development (Roco 2004). Yet, there is evidence suggesting that nanotechnology-enabled products are appearing at a growing rate in the marketplace. For example, the Project on Emerging Nanotechnologies (PEN 2009b) has catalogued more than 1,000 nanotechnology-based consumer products worldwide, up from the 212 products identified in March 2006. Of the current consumer nanotechnology products, about 54 percent originate from the US including nanotechnology-enabled products in cosmetics, clothing, sporting equipment, electronics, and automotive applications (PEN 2009a). Significant shares of these current consumer-oriented articles are products which might be considered as incremental rather than as radical innovations (Freeman 1982), for example, applications of passive nanostructures such as nanosilver particles (reported in about one-fifth of the nano-enabled products marketed by US firms) or nano-engineered textiles (found in stain-resistant or odor-absorbing clothing). However, consumer-oriented applications of nanotechnology are only one of the ways through which nanotechnology innovations are commercialized. The translation of nanotechnology discoveries to new applications occurs at multiple steps in the nanotechnology value chain, including in the design and manufacture of nanomaterials, the production of intermediate inputs such as electronic components and nanowires, the development of finished nanotechnology-enabled products, and building tools and instruments for nanotechnology (Lux Research 2007). Within this nanotechnology value chain, there are other companies working on applications involving more complex active nanostructures perhaps still in development or in early trial stages, including targeted drugs and chemicals, energy storage devices, nanoelectromechanical, and nanobio devices. Such applications can be viewed as more radical in nature, which, if introduced at scale, are likely to have greater economic impacts—and perhaps also raise new issues related to risk management since active nanostructures have the capability to change or evolve their states during operations (Subramanian et al. 2009). Such innovations may also be associated with different innovation strategies and likelihoods of success. In some cases they may be reflected in entrepreneurial spinoffs. Wang and Shapira (2009) identified some 230 new nanotechnology-based venture start-ups formed in the US through to 2005, with about one-half being companies that had spun-out from universities. Fernández-Ribas (2009) also finds an increase in small company World Intellectual Property Organization (WIPO) patent applications. Other research highlights the importance of large firms. Laredo (2008) and Rothaermel and Thursby (2007) argue that a distinctive attribute of nanotechnology is the early involvement of large incumbent firms, which differs from the biotechnology paradigm of innovation emerging from small start-ups often with a university relationship (Laredo 2008; Rothaermel and Thursby 2007). These incumbent firms may be involved both in the commercialization phase, in nano-enabled incremental improvements to existing products, and in the research phase with respect to distinctive new applications.

We posit that the entry of corporations into nanotechnology commercialization, despite the presence of multi-national supply chains, will reflect some of the generalized characteristics of the national innovation system of the country in which these corporate entities are embedded. We are led to this proposition by the rise of research over the last 20 years into the distinctive characteristics of national innovation systems (Nelson and Winter 1982; Edquist 1997; Lundvall 1992). These works emphasize system and evolutionary perspectives including the role of learning within and between firms, interactions among enterprises and institutions, and systems of knowledge development and innovation. The result has been the advance of attention to country-level differences in organization and procedure, which help in better understanding the knowledge-based strategies of firms, the linkages of companies within the national system, and the type of commercialization strategies that are developed.

More recently, attention has turned from national to global perspectives on innovation. The role of information technology, multinational enterprises and supply chains, and the rise of technologically capable global competition have brought forth a view that innovation takes place in an increasingly "flat world" of greater leveling across nations and more international similarity in technological capability (Friedman 2005). This position also has been described as the "death of distance" (Cairncross 2001), in that the use of information technology enables innovations from any location to enter the market; they do not have to be in a particular developed or leading region or nation to do so. In the same vein is the expanding consideration of "open innovation" initiated by Chesbrough (2003) which stresses the importance of new business models (other than traditional company-held intellectual property protection) for knowledge and of being connected to global and multiple diverse knowledge sources. Operating within this global context are sectoral innovation systems composed of heterogeneous networks of multinational companies, suppliers, customers, and knowledge sources including corporate R&D units and external linkages with universities, government laboratories, and other innovation companies. (Malerba 2005) Sectors have been classified as being science-based, scale-intensive supplier focused, and knowledge-intensive services according to whether they have engage in corporate innovation. (Pavitt 1984) It has been pointed out that the international component of R&D activities and their influence on the technological activities varies greatly among the world's largest manufacturing firms (Patel and Pavitt 1991) and, as has recently been found, R&D in specific sectors such as automobiles and wireless telecommunication exhibits a decisive home bias (Cohen et al. 2009).

Nanotechnology is certainly emerging in this era of internationalization, which might lead one to anticipate a more or less disseminated activity in this technology across multiple nations. On the other hand, the complexity and multidisciplinarity of nanotechnology could lead to streams of R&D activities in selected locations each with specific patterns rather than a more globalized distribution. For example, Fernández-Ribas, and Shapira find that in the mid-2000s large US MNEs active in nano-patenting concentrated their inventive activities at home and in a relatively small set of other advanced countries based on scientific and technological capabilities rather than dispersing such activities globally (Fernández-Ribas and Shapira 2009). Nanotechnology R&D activities including research publication and patenting have continued to expand internationally in recent years (see for example Youtie et al. 2008). Nonetheless, we suggest that the distinctive characteristics of national innovation systems matter in the commercialization of nanotechnology, including but not limited to the scientific, technological, organizational, and user characteristics of those innovation systems. This type of systemic influence has been observed in previous technological waves. For instance, at the level of the regional innovation system, Saxenian describes how the rise of the microcomputer and minicomputer in the Bay Area and Boston, respectively, were influenced by the organizational structures of the respective regional innovation systems. Such distinctive profiles have appeared with respect to nanotechnology (Saxenian 1994). China's nanotechnology enterprise is based on its strengths in chemistry and physics, with many nascent companies being closely connected, through ownership or investment, with universities. In contrast, the US and the UK have greater strengths in the biological and life sciences, while diverse patterns of nanotechnology commercial activity among large corporations and spinoffs are evidenced (Porter et al. 2008; Shapira and Wang 2009; Tang et al. 2009).

In this paper, we propose that the shift in nanotechnology from research to commercialization, although occurring in a period of globalization and internationally networked science, is influenced at least in part by the national innovation systems of the countries in which the R&D activity is embedded. We will explore the shaping of national innovation systems by beginning with an overview of corporate entry into nanotechnology. We will show that a shift, albeit not stark, can be detected from aggregate and country-level statistics comparing publication and patent activity. Our analysis will then shift to a comparative national perspective. Here we will focus on national differences as represented in several commercialization characteristics of corporations that appear in the WIPO nanotechnology-related patents. These include: the ratio of patent applications to scientific publications, time period of entry, technological specialization, size, non-corporate assignees, and cross-national linkages. We acknowledge that patents are but one measure of commercialization and are not without problems. On the other hand, studies of prior emerging technologies have found publications and patents to be early indicators of commercial activity (Shapira et al. 2003). The results will show that national innovation systems characteristics are significant factors in the commercialization shift of nanotechnology, notwithstanding the global spread of nanotechnology R&D and the complementary role of international invention linkages.

2 Data sources

Our definition of nanotechnology-related publications and patents draws on the Georgia Tech global publication and patent database. This database results from a multi-stage Boolean search approach used to identify nanotechnology-related publications and patents based on keywords, journals, and patent classes (Porter et al. 2008). This search strategy is applied to publication records (Science Citation Index, Web of Science, Thomson Scientific) and global patent records (IISC PatStat). In the case of patents, these searches include cross-classifications such as US class 977 and WIPO class B82B. The database covers the time period 1990–2008.

New datasets for corporate activity are created based on clean up and classification of author affiliations in publications and assignees in patents. Text mining software (VantagePoint) and appropriate hardware make possible this type of analysis involving processing of large datasets. Patent families are reported to avoid duplication. A summary of these extracted corporate activity records is shown in Table 1.

The main limitation in bibliometric and patent analyses is data coverage in the original data sources (ISI-WoS and Patstat). In particular, some country data for assignees is missing, although we still are able to assign 87 percent of patent application or grant records to a country. Thus, the patent analysis presented in the following section refers only to corporate assignees with country information.

Table 1 Basic statistics on nanotechnology data sources, worldwide (all reporting countries), 1990–2008

	Publications	Patents
Source	ISI-WoS	Patstat
Unit of analysis	Publication record	Patent record
# Records[a]	648,195	92,463
# Organizations (all types)[b]	51,192 (author affiliations)	14,739 (assignees)

Data sources cover only part of 2008 for patents (until July 2008)

Source: Based on Georgia Tech global nanotechnology databases

[a] Before data clean up

[b] Before data clean up, includes authors' affiliations in publications, patent assignees in patents, and all type of unique organizations in the establishments database

3 Overview of corporate entry into nanotechnology through patents and publications: 1990–2008

Our preliminary analyses of corporate activity show that some 17,600 companies worldwide (and 5,440 US companies) have published about 52,100 scientific articles and applied for about 45,050 patents in the nanotechnology domain from 1990 to 2008. About 18,000 nanotechnology patents were granted to corporate assignees in the same time period. This figure should be interpreted with care in that it does not account for firm exits (due to firm failure) or "unpublished" firms that work in nanotechnology but lack a record of research articles or patent applications.

Corporate entry and activity in nanotechnology publication and patenting has expanded significantly over the past two decades. Corporate publications have grown at a 26 percent average annual rate over the 1990–2008 time period while patent grants have grown by a 23 percent average annual rate and applications by a 20 percent average annual rate. US companies remain the largest producers of corporate publications and patents worldwide. US corporate activities in nanotechnology have grown in absolute terms in the 1990s and 2000s. However, as engagement in nanotechnology has developed internationally, the relative worldwide share of US companies has declined as corporations based in other countries have expanded their entry into nanotechnology and increased their publication and patent outputs.

A simple analysis of the relationship between corporate nanotechnology publications and patent applications indicates a relative shift in emphasis from discovery in the 1990s to applications, particularly in the years since 2003 (see Fig. 1).

In the early 1990s (1992–1994), corporations were producing worldwide about 2.9 times as many nanotechnology publications as patent applications, indicating a focus on research and new knowledge development in the nascent nanotechnology domain. However, by the latter part of the current decade (2005–2007), corporations were producing worldwide an average of 1.3 patent applications for each publication, suggesting that companies are now focusing relatively more attention on the application of knowledge. The influx of publicly accessible USPTO patent applications starting in 2001 may well be influential in the rapid rise in patent applications from 2001 to 2003; however, even if we focus our analysis solely on WIPO patents, thereby excluding new USPTO patent applications, we will see that this relatively steep increase in nanotechnology patent applications

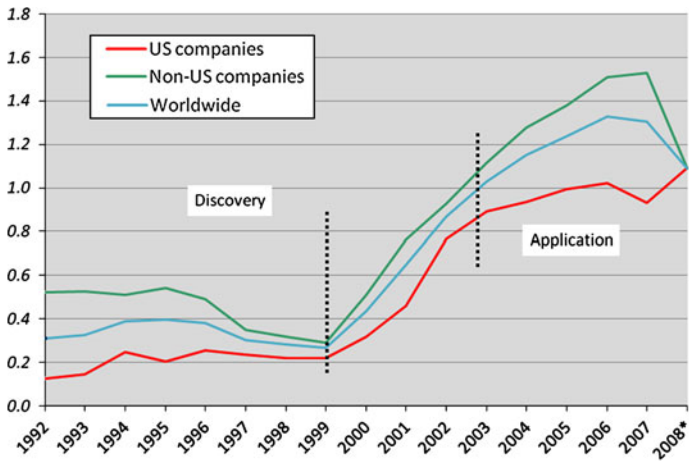

Fig. 1 Ratio of corporate nanotechnology patent applications to publications, 1992–2008. *Notes*: Data for 2008 is annualized for patents; *Y*-axis = ratio of corporate nanotechnology patent applications to corporate nanotechnology publications by year. *Source*: Georgia Tech global nanotechnology databases

in the early 2000s persists, suggesting that the USPTO's publishing of patent applications is not the sole factor in the increase in nanotechnology patent applications (see Fig. 2).

The ratio of patent applications to publications is typically lower for US companies compared with their non-US counterparts. In other words, US corporations on average tend to publish relatively more articles compared with their output of patent applications than non-US corporations. More analysis is needed to interpret this trend, which could reflect differences in databases (for example, variations in the publication databases in capturing English language vs. non-English language articles), research intensity, publication culture, patent quality and technical focus, and patent strategy. This shift in the relative balance of corporate activity between publications and patent applications suggests that a transition in corporate emphasis from discovery to application in nanotechnology may be underway.

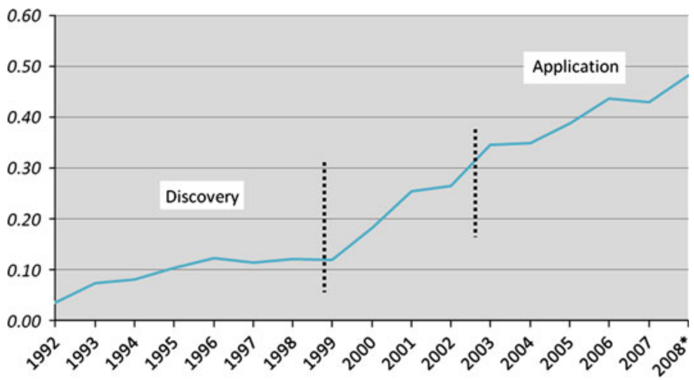

Fig. 2 Ratio of WIPO patent applications to scientific publications, for companies of all countries, 1992–2008. *Notes*: Data for 2008 is annualized for patents; *Y*-axis = ratio of corporate nanotechnology patent applications to corporate nanotechnology publications by year. *Source*: Georgia Tech global nanotechnology databases

The next section explores factors that may be lying behind the emergence of corporate applications.

4 Nanotechnology innovation factors in the shift to commercialization

In this analysis we examine the proposition that the distinctive factors of nations play a role in nanotechnology innovation. This is examined through country level data for 46 countries with five or more nanotechnology patent applications over the 1992–2008 time period. We focus on Patent Cooperation Treaty (PCT) patents administered by the WIPO in this analysis to account for biases in using country or regional patent office data. PCT patents may be considered to represent intellectual property with broader international relevance, with WIPO furnishing non-binding judgments about the novelty, applicability, and inventiveness or non-obviousness of the patents in the PCT process.

We seek to explain country-level differences in nanotechnology patents with our dependent variable commercialization activity (COMMACT) being the number of corporate PCT patent applications in the 2003–2008 time period, which is the period after which the "shift" to application is observed. We also examine the ratio of nanotechnology corporate publications and WIPO patent applications to all publications and patent applications in a country (CORPACT) as a measure of the corporate activity intensity of the country. Figure 3 shows the distribution of corporate patents and publications for some country examples in a log scale scatterplot. Four major groups are apparent. The first is comprised of three large countries in terms of corporate publishing and patenting: the US, Germany, and Japan. The second group represents a diverse range of large and medium-sized countries in terms of corporate publishing and patenting in the nanotechnology domain, including France, the UK, South Korea, and China as well as Israel. The next group includes smaller countries with respect to nanotechnology corporate entry such as South Africa and Brazil. The final group is comprised of micro countries relative to nanotechnology corporate entry such as Malaysia, Slovenia, Iceland, and Luxembourg (see Fig. 3).

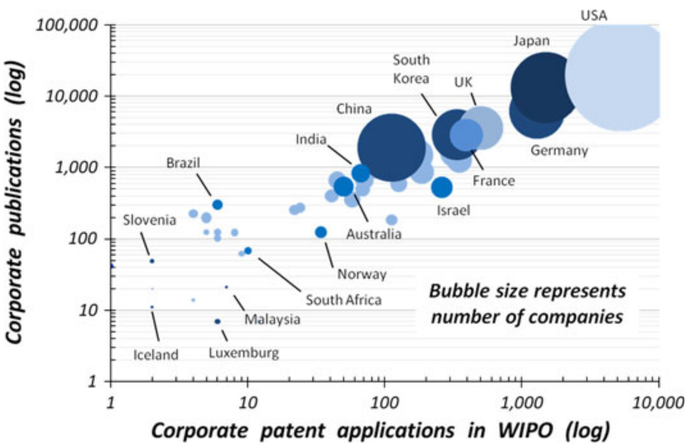

Fig. 3 Corporate publications by corporate patent applications (WIPO) 1992–2008. *Note*: *X* and *Y* axis are log scales; *labels* are shown for only some country examples; *bubble shading* does not represent any measure; partial year 2008 is annualized for patents. *Source*: authors' analysis

These proxies for nanotechnology corporate activity are hypothesized to be a function of three factors. These reflect general national innovation system characteristics across the broad range of goods and services including, but not limited to, nanotechnology. The variables in this category include (1) LGERD06: gross expenditures on R&D (purchasing power parity, US dollars),[2] (2) HIGHINC: classification of the country as a high income economy by the World Bank,[3] and (3) TRADE: trade openness as defined by the sum of merchandise exports and imports divided by the value of GDP (World Trade Organization, and World Bank GDP estimates). Certainly, the characterization of national innovation systems is only possible to the extent allowed by the data available for the countries in our dataset. In this regard, two caveats apply for using such a set of variables. LGERD06 comprises basic and applied research expenditures, which may raise an issue of endogeneity if corporate applied research was fostered by a national innovation system as a response to positive signals of technology development (in this case nanotechnology.) Alternative variables, such as government and higher education R&D expenditures (as reported by UNESCO Institute of Statistics) were explored, yet missing data impede their use in our research. On the other hand, TRADE should be considered only a description of the extent to which a country is integrated into the global economy and not as a characterization of all possible country strategies for internationalization.

The second set of variables characterizes the attributes of nanotechnology corporate entry within each country. One such variable is LARGENT: the country's share of nanotechnology large enterprises, defined by the number of corporate entries (i.e., with either nanotechnology publications or patents between 1992 and 2008) that are large, as reported by the Forbes Global 2000 list, divided by the total number of nanotechnology corporate entries for the country. A second such variable is EARLYENT: the number of enterprises entered into the nanotechnology domain through publications or patents early in the development of nanotechnology, i.e., in the 1992–1999 time period, as a percentage of all enterprises entered into the nanotechnology domain across the full 1992–2008 time period. Such early entry would presume to give a region early advantage in the production of nanotechnology research and commercialization. This variable is represented by the share of corporate entry in the 1992–1999 time period compared to corporate entry over the entire period of study, 1992–2008.

The third set of variables has to do with the extent to which certain nations "specialize" in particular aspects of nanotechnology, such as nanoelectronics or nanobiotechnology. We examine specialization in research, proxied by the concentration or dispersion of publications in the most common nanotechnology related "macro disciplines" (Porter and Youtie 2009)—materials science, chemistry, physics, biomedical science, engineering science, computer science. Specialization in commercialization is measured by the concentration or dispersion of patent applications across the most common three-digit nanotechnology related international patent classification (IPC) classes: A61 (Medical or Veterinary Science); H01 (Basic Electric Elements); G01 (Measurement, Testing); C08 (Organic Compounds); C01 (Chemistry, Metallurgy); B01 (Physical, Chemical Processes). We have developed overall normalized Herfindahl-based measures of specialization across these macro disciplines (SCHERFN) and IPC classes (IPCHERFN). We are focusing on these six macro disciplines and IPC classes to enable similar treatment of large and small patenting countries.

We also examine the extent to which a country's nanotechnology system has reached sufficient levels of specialization to attract citations. Citations are often viewed as a

2 Obtained from UNESCO Institute for Statistics (UNESCO 2010).

3 Obtained from World Bank databases (World Bank 2010).

measure of quality and influence in a particular field, within the constraints of limitations such as self-citations, negative citations, and referee additions. Previous research (Youtie et al. 2008; Glanzel et al. 2003) suggests that citation differentials represent inter-country differences in nanotechnology. In this analysis, we present the variable NANOCITE to measure citations as the percentage of all nanotechnology publications in the country that are highly cited. Highly cited in this analysis means the nanotechnology publication has attracted at least 25 citations in the period 1992 through 1999.

The model also incorporates a variable that represents the rival hypothesis to the national innovation system framework. This variable measures the extent to which countries have inventor-based linkages outside their boundaries. Because inventor address information is most complete for US patent applications, our proxy (USINV) is focused on patents filed by enterprises in non-US countries with at least one US inventor, or patents filed by US-based enterprises with at least one non US-based inventor. It should be noted that these cross-national collaborations of inventors may well take place within the same enterprise or corporate group.

Table 2 presents descriptions of each of the variables in our model. Table 3 summarizes the distribution of these measures. An examination of the distribution of these variables indicates that the dependent variables follow the standard power distribution, so we normalized them through log transformation for our first two statistical models. We also have conducted multicollinearity analyses, including variance inflation factor (in OLS models) and correlation matrix examination; these data suggest that measures are not highly intercorrelated (see Table 4). On the other hand, general F-tests allow rejecting the null hypothesis on the effect of all independent variables as a group in the two OLS models. For the rest of the models, alpha test statistics were assessed to understand whether the response variable is over-dispersed and is not sufficiently described by a simpler poisson distribution.

Table 5 presents the results of the regressions. In terms of nanotechnology national innovation systems (NIS) measures, early entry (EARLYENT) is a statistically significant, yet still a slight driver of overall corporate entry (CORPACT), though not corporate commercial activity (COMMACT), suggesting that early entry is primarily through publication-based research and discovery rather than patent application. The percentage of large enterprises (LARGENT) is not a significant factor in distinguishing countries with respect to nanotechnology corporate activity in general or commercialization in particular. Specialization measures are not significant on the patent application side (IPCHERFN) in any model, but are significant on the publication side (SPHERFN) when looking at overall corporate activity of the country in nanotechnology. This finding suggests that higher levels of specialized research, as opposed to widespread research, are an important factor in corporate entry. Citations for nanotechnology publications (NANOCITE) also have a small positive effect on both commercialization and corporate activity, in our four models, yet that effect is not significant.

General characteristics of the overall national innovation system are also significant in these models. The overall corporate entry into nanotechnology through publications and patent applications (CORPACT) and corporate nanotechnology commercialization through patent applications (COMMACT) are associated with high-income countries (HIGHINC). Countries that invest more in research and development (LGERD06) see a positive effect on nanotechnology commercialization (COMMACT) but a negative effect on general corporate activity (CORPACT). The degree of openness of the economy (TRADE), one of the characteristics of the NIS which indicates the role of the economy in global

Table 2 Variables and description

Variable	Description	Observations
COMMACT and LCOMMACT	Nanotechnology commercialization activity and its natural logarithm, calculated as: COMMACT = number of corporate patent applications in WIPO, 2003–2008	Dependent variable in models 1 and 3; missing values are recoded as 0
CORPACT and LCORPACT	Share of corporate activity in nanotechnology and its natural logarithm, for period 1992–2008, calculated as: CORPACT = [Corp publications + Corp WIPO patents]/[Country publications + Country WIPO patents] * 100	Dependent variable in models 2 and 4; missing values are recoded as 0
LARGENT	Percentage of country Forbes 2000 companies in country's corporate entries for period 2003–2008	Based on Forbes 2000 list published by Forbes magazine in 2008
EARLYENT	Percentage of early corporate entries for the country, calculated as: EARLYENT = [number of enterprises entered in the nanotechnology domain in the 1992–1999]/[total number of enterprises entered into the nanotechnology domain in 1992–2008]	Missing values are recoded as 0
LGERD06	Natural logarithm of the Gross Domestic Expenditure on Research and Development (GERD) in US$ million PPP in 2006. Source: OECD and UNESCO	Missing values are recoded as 0
HIGHINC	OECD classification of developed nations	1 = countries classified as high income by OECD (member and nonmember countries)
USINV	Share of WIPO corporate patent applications with at least one inventor reporting US location in period 1992–2008. For the US, this variable measures the share of patents that report at least one inventor outside the US	Missing values are recoded as 0
IPCHERFN	Normalized Herfindahl Index calculated for top-6 3-digit IPC classes in WIPO nanotechnology corporate patent applications in period 1992–2008	The top-6 3-digit IPC classes in WIPO nano-patents are A61 (Medical or Veterinary Science), H01 (Basic Electric Elements), G01 (Measurement, Testing), C08 (Organic Compounds), C01 (Chemistry, Metallurgy), and B01 (Physical, Chemical Processes)
SCHERFN	Normalized Herfindahl Index calculated for top-6 megadisciplines in nanotechnology corporate scientific publications in period 1992–2008	The top-6 megadisciplines in ISI-WoS nano corporate scientific publications are Materials Science, Chemistry, Physics, Biomed Sciences, Computer Science, Engineering
NANOCITE	Percentage of country publications between 1992 and 1999 with 25 or more citations	Citations from year of publication until December 2008 are considered

Table 2 continued

Variable	Description	Observations
TRADE	Sum of merchandise exports and imports divided by the value of GDP, all in current US dollars. Source: World Trade Organization and World Bank GDP estimates	

The data source for variables is the Georgia Tech global publication and patent database, otherwise indicated. We have applied two sets of models for each of the two dependent variables. The first set is ordinary least squares (OLS) regression with a logged dependent variable. The second set is negative binomial regression to account for left hand censoring of publication and patent application counts. Table 5 presents the results. The models are observed to be statistically significant and consistent across OLS and negative binomial models

Table 3 Means and standard deviations

Variable	Obs	Mean	SD	Min	Max
COMMACT	46	198.85	627.55	0.00	4051.00
LCOMMACT	46	3.22	2.10	0.00	8.31
CORPACT	46	12.02	16.23	1.80	91.03
LCORPACT	46	2.09	0.82	0.59	4.51
LARGENT	46	4.91	5.93	0.00	25.00
EARLYENT	46	19.70	11.50	0.00	42.39
USINV	46	0.16	0.18	0.00	0.67
IPCHERFN	46	0.12	0.12	0.01	0.47
SCHERFN	46	0.18	0.13	0.09	1.00
NANOCITE	46	9.07	5.45	0.00	28.57
LGERD06	46	8.48	1.87	4.10	12.76
HIGHINC	46	0.70	0.47	0.00	1.00
TRADE	46	73.61	59.66	0.00	366.81

N of cases = 46

commercialization of goods, has a significant, small negative effect only when modeling the overall nanotechnology corporate activity (CORPACT) as dependent variable.

While these national innovation system characteristics are significant, we also observe that the rival internationalization measure included in this analysis is also significant. There is a positive and significant effect of out-of-country inventor collaborations in nanotechnology patents (USINV) on corporate commercialization. This effect is not significant when considering both nanotechnology corporate publications and patent applications as a share of all publications and patent applications.

5 Summary and conclusions

This research has examined the commercialization of nanotechnology, as represented by corporate entry through publications and patent applications, and in the context of national innovation systems. The results presented here are subject to some limitations. Our

Table 4 Correlation matrix

	COMMACT	LCOMMACT	CORPACT	LCORPACT	LARGENT	EARLYENT	USINV	IPCHERFN	SCHERFN	NANOCITE	LGERD06	HIGHINC	TRADE
COMMACT	1.00												
LCOMMACT	0.58	1.00											
CORPACT	0.05	0.01	1.00										
LCORPACT	0.21	0.33	0.82	1.00									
LARGENT	0.02	0.14	0.21	0.13	1.00								
EARLYENT	0.27	0.55	0.12	0.39	0.10	1.00							
USINV	0.05	0.02	0.08	0.10	0.11	−0.17	1.00						
IPCHERFN	−0.21	−0.58	0.10	0.01	−0.10	−0.32	0.38	1.00					
SCHERFN	−0.10	−0.24	0.67	0.40	0.43	−0.14	0.19	0.26	1.00				
NANOCITE	0.30	0.43	−0.02	0.36	−0.17	0.56	−0.16	−0.21	−0.34	1.00			
LGERD06	0.52	0.77	−0.34	−0.19	0.05	0.41	−0.2−5	−0.66	−0.34	0.22	1.00		
HIGHINC	0.19	0.44	0.33	0.64	−0.01	0.37	−0.10	−0.33	0.05	0.55	0.07	1.00	
TRADE	−0.17	−0.08	−0.18	−0.12	0.36	−0.08	0.03	0.03	−0.03	−0.02	−0.17	0.08	1.00

N of cases = 46

Table 5 Models of national innovation system factors and nanotechnology corporate entry

Variables	OLS models		Negative binomial models			
	(1) LCOMMACT	(2) LCORPACT	(3) COMMACT	LNALPHA	(4) CORPACT	LNALPHA
Nano corporate entry						
LARGENT	0.04	0.01	0.04		0.00	
	(0.03)	(0.02)	(0.03)		(0.02)	
EARLYENT	0.02	0.02**	0.01		0.02***	
	(0.02)	(0.01)	(0.01)		(0.01)	
Nano specialization						
IPCHERFN	−0.13	0.02	−1.37		−0.42	
	(1.85)	(1.00)	(1.70)		(1.00)	
SCHERFN	−1.40	2.01**	−1.19		1.87**	
	(1.51)	(0.81)	(1.27)		(0.80)	
NANOCITE	0.01	0.02	0.03		0.00	
	(0.04)	(0.02)	(0.03)		(0.02)	
National innovation system						
LGERD06	0.80***	−0.12*	0.80***		−0.18***	
	(0.11)	(0.06)	(0.09)		(0.06)	
HIGHINC	1.63***	0.87***	1.66***		0.96***	
	(0.43)	(0.23)	(0.32)		(0.25)	
TRADE	−0.00	−0.00*	−0.00		−0.00**	
	(0.00)	(0.00)	(0.00)		(0.00)	
Out-of-nation nano-collaborations						
USINV	3.08***	0.40	3.14***		0.08	
	(0.86)	(0.47)	(0.77)		(0.49)	
Constant	−5.62***	1.63**	−5.13***	−0.88***	2.49***	−2.02***
	(1.25)	(0.67)	(1.01)	(0.26)	(0.60)	(0.34)
Observations	46	46	46	46	46	46
Adjusted R-squared	0.80	0.61				
Pseudo R-squared			0.205	0.205	0.191	0.191

Standard errors in parentheses; *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$

measure of corporate entry into nanotechnology through publications and patents may be subject to an overestimation of corporate presence, because it does not account for firm failure (which would particularly affect small firm presence), while at the same time it may also underestimate entry of corporations that do not publish papers or patent applications. Thus the overall counts should be interpreted with caution. As well, the figures used in this paper represent aggregations of nanotechnology research and patent application measures of corporate entry at the national level. They do not yet capture significant firm or regional level variations (see for example Shapira and Youtie 2008). In addition, the paper focuses on the juxtaposition of national innovation systems relative to globalization; it does not fully consider other systems of innovation that are important in nanotechnology commercialization, such as particular sectoral innovation systems (e.g., food or electronics) or international value chain innovation systems. These other innovation systems are important but challenging to measure within the constraints of the datasets used in this paper. Moreover, our analysis is based on WIPO patents, to facilitate country-to-country comparisons, so other patterns of national patent activity that could be discerned from nanotechnology applications in the country's patent office are not reflected in these data. An analysis of a country's patent office applications could indicate that other factors are at work in that country's corporate entry into nanotechnology. Furthermore, our data do not include all the variables that would enable full modeling of how changes in national and nanotechnology characteristics may affect results. We are able in this paper to carry out a preliminary exploration of how national innovation system and international indicators presented in this research can be used to understand nanotechnology corporate research and patenting outcomes.

The first proposition of a shift from discovery to commercialization in nanotechnology is observed in graphical trend analysis. This shift is especially evident in countries outside the US which have substantially higher levels of commercial activity since 2003 than before 1999. There is also evidence of this shift in the regression models. Although we do not employ the ratio of applications to publications as our dependent variable in these models, in part because countries with low activity are overemphasized under this measure, we can see that those countries with a high proportion of enterprises that have entered into nanotechnology in the early 1992–1999 time period, are more likely to have a higher share of nanotechnology corporate activity in the later period than countries without this share of early activity. In other words, countries that have invested in or otherwise supported a high share of enterprises early in the timeline of nanotechnology R&D are more likely to see higher levels of commercial activity in the later period.

The second proposition suggests that the national innovation system characteristics of a country are significant to the entry by its corporate sector into the nanotechnology commercial domain. The models indicated that the general characteristics of the national innovation system—developed country status—had a positive and significant effect on both corporate commercialization (i.e. patent applications) and corporate R&D (patent applications and publications). Expenditures on R&D also had a positive effect on nanotechnology patent applications, but its relationship with all corporate activity was negative. The trade variable, measuring the reliance of an economy on other economies for R&D, is also negatively associated with nanotechnology commercialization. It may be that some small countries are entering the nanotechnology domain directly through the corporate sector without involvement of other sectors such as universities or government laboratories.

Likewise, countries that specialize in a particular research area are more likely to have a higher share of corporate activity, perhaps because it is more applied research. Specialization in nanotechnology research seems to be important for development of a large corporate sector in nanotechnology. We do not find this to be the case for specialization as measured by patent classes, perhaps because of multiple assignments of IPC classes to a given patent. This is an early signal that the influence of sectoral innovation systems is not yet as prominent in nanotechnology applications as might be expected, although a more fine-grained or segmented approach may be necessary to fully uncover sectoral innovation patterns. At the aggregate level, however, we do not see that sectoral specialization is important at this point in time. This is an interesting finding because one might expect that specialization would be concomitant to being able to commercialize in a particular application area. While this is the case for publications, it is not the case for patenting.

Regarding the size of the enterprise, it was suggested in the literature that large incumbents dominated early nanotechnology commercial activity. However, our research supports the view that nanotechnology commercialization is relevant to small as well as large enterprises at this juncture in its development.

Our findings highlight the ongoing importance of national innovation system policies and frameworks in affecting trajectories and locations for commercialization in this emerging technology domain. In addition to broad-based national policies for investing in R&D, our results signal the potential roles in nanotechnology commercialization of policy efforts to encourage early corporate entry and positioning and specialized corporate R&D (through mechanisms that may include foresight and road-mapping, corporate networking and information exchange, R&D incentives, enterprise startups, and targeted public–private innovation partnerships). Yet, this focus on national innovation systems should not let us overlook the important role of international factors such as cross-border knowledge networks and supply chains in the commercialization of nanotechnology. Our model indicates that countries with a high proportion of foreign inventors are more likely to have higher rates of commercialization in nanotechnology. The effect of international collaborations in patent applications on corporate commercialization suggests that countries with either more multinational corporations (and global research centers) or more dynamic and collaborative firms (e.g., global start-ups) are more likely to shift from discovery to technology application in nanotechnology.

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