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Technological diversity, scientific excellence and the location of inventive activities abroad: the case of nanotechnology

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Abstract. Our contribution to the expanding literature on the globalization of research and innovation is to investigate the extent to which sector-specific developments in an emerging technology (such as increasing interdisciplinarity and complexity) affect inventive activities developed abroad. We look at how technological diversity and scientific excellence of host countries in the field of nanotechnology affect the development of inventive activities by US multinational companies (MNCs). We identify the most active US-based MNCs in nanotechnology-related patenting and examine location decisions of these companies and their international subsidiaries. Econometric results confirm our hypothesis that the technological breadth of host countries positively influences the expected number of inventions developed abroad by US MNCs. Science capabilities of countries also have a positive impact on the decision to invent abroad, while the influence of market specific factors is less clear. We interpret these results as suggesting that host country science capabilities are important to attract innovative activities by MNCs, but as the interdisciplinary and convergent nature of nanotechnology evolves, access to a broadly diversified knowledge base becomes important in increasing the relative attractiveness of host locations.

Keywords: Multinationals, Innovation, Location, Patents, Nanotechnology.

JEL Classification: F23, O32, L22.

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1. Introduction

In recent years there has been growing theoretical and empirical debate about the types of research and innovation activities that multinational corporations (MNCs) can and do perform abroad. According to new decentralized competence models (Cantwell 1995; Blanc and Sierra 1999; Dunning and Narula 1995; Florida 1997; Kuemmerle 1999; Zanfei 2000; Kumar 2001; and Frost 2001), decisions about what research and innovation activities to undertake abroad now occur in an era characterized by increased globalization of competencies in science and technology. With greater choice about where to locate high-potential research and innovation, the location selection process becomes more complex and increasingly sensitive to the characteristics of host country innovation systems.

Empirical papers that have examined how local research environments affect the internationalization process of research and innovation generally find that countries with stronger scientific and technological capabilities (Guellec and van Pottelsberghe 2001; Le Bas and Sierra 2002; Feinberg and Gupta 2004; Belderbos 2006; Thursby and Thursby 2006; Ito and Wakasugi, 2007) and countries which provide certain guarantees regarding intellectual property protection methods attract more inventive activities by foreign MNCs (Branstetter et al. 2005; Hagedoorn et al. 2005; Wakasugi and Ito 2007).

While this research has improved understanding about how the nature of local innovation systems affects the internationalization of R&D, several questions remain unanswered. For example, we do not know much about how systems respond to the changing stages of emergence of a given technology. Nor do we know enough about how the increasing sophistication of a technology affects location decision processes and the attractiveness of host innovation systems. In this paper, we try to answer these questions for the emerging field of nanotechnology.

As a current emergent domain of new technology, we expect nanotechnology to be subject to the latest strategies of R&D management and location adopted by MNCs. But there might be some phasing, as nanotechnology develops from initial research to simple applications to more sophisticated and complex products and devices. We postulate that as the nanotechnology field evolves, corporations will likely adopt the latest development techniques at the frontier of new MNC research and innovation strategies, seeking the attractiveness of locations with a strong research base in nanotechnology. Yet, the increasing interdisciplinary and convergent character of nanotechnology may come into play as the technology becomes more sophisticated. Local innovation systems with a deep array of diverse disciplinary strengths and highly-qualified capabilities might then be attractive locations to conduct complex research.

To test our ideas, we construct a balanced panel of US-owned corporations with nanotechnology activities during 1997-2006 and estimate a series of count-based models on the number of patents invented in host countries by these companies. The data come from several sources, including a rich database of nanotechnology patents built using MicroPatent and INPADOC data, publication records from the Science Citation Index (SCI) database in the Web of Science, USPTO patents assigned to corporate companies in all technological fields, and macroeconomic data from the World Bank. Due to the longitudinal nature of our data, we are able to estimate dynamic relationships between the dependent variable and explanatory variables.

Our results contribute to a series of interesting empirical findings. We find that technological diversity in nanotechnology, measured by the lagged value of the reciprocal of the Gini coefficient, increases the expected number of patents invented by a US MNC in a foreign country. Scientific strength, measured by the average number of science and technical publications originating in a host country, is also significant and positively associated with the quantity of inventions a US MNC develops abroad. The level of scientific excellence in nanotechnology, measured as the weighed number of publication citations in the five years prior to the inventive process, also increases the expected number of patents invented abroad, but to a lesser extent. By contrast, the influence of traditional market driven factors, such as market size, is less clear.

The paper is organized as follows. Section 2 explains our hypothesis, research questions and empirical model. Section 3 reviews data sources and data characteristics. Section 4 describes estimation methods and econometric results. Section 5 closes the paper with some concluding comments and policy implications.

2. Analytical framework

Modern theories about the reasons behind the globalization of research and innovation point to the changing role of MNC location strategies.[1] Florida (1997), for example, argues that global R&D not only serves the purpose of creating "listening posts" to monitor the scientific and technological capabilities of domestic firms and universities, but also for creating knowledge "generating stations" which generate new scientific and technological capabilities. Kuemmerle (1999) adds that global R&D may be viewed as a way to adapt technology generated at home to local production (which he coins as "home-based exploiting" R&D), or as a way to increase the productivity of domestic R&D (denoted as "home-based-augmenting" R&D).

Dunning and Narula (1995) associate this process of increasing home-based capabilities with the search for strategic assets that are specific to other firms and locations. The intrinsic tacitness of these activities and the firm's desire to absorb as much local knowledge as possible implies that affiliates engage into more sophisticated R&D activities in locations which exhibit a comparative technological advantage relative to the home location of the MNCs. Cantwell (1995) suggests that MNCs locate

[1] See Narula and Zanfei (2004) for a recent survey.

innovation activities abroad to take advantage of agglomeration economies and benefits from locational divisions of labor. More recently, Narula and Zanfei (2005) and Criscuolo et al. (2005) suggest that both the evolving nature of host and home innovation systems may affect the types of innovation firms develop abroad.

In this paper, we seek to contribute to this literature by suggesting that under conditions of increasing global competitiveness across locations, some new explanatory factors should be explored in order to better understand firms' location decisions. We first propose that the internationalization of inventive activities may vary according to the stage of technological trajectory. It is plausible that the benefits of polycentric R&D are related to the development stage of a technology. Hagedoorn and Narula (1996) state that in industries characterized by rapid technological developments and high uncertainties, organizational flexibility and speed of information are vital. Archibugi and Michie (1995) observe that this is particularly true in industries in their infant states, where there is greater need for new knowledge and for sharing it. Thus, as a technology evolves, the need for foreign knowledge may change, based on what companies have learned in their early forays, their research and investment strategies, the regional availability of advanced technological capabilities, and the balance between knowledge-seeking and knowledge-protection.

Traditional location factors such as market size (Vernon 1966) may attract inventive activities that are more applied in nature. Such factors may be important where innovations are incremental and close to market but less important where more exploratory research is being undertaken. Having strong scientific capabilities may attract inventive activities with an explorative component in the development stages of a technology. However, in more mature stages, more sophisticated factors such as scientific excellence and a diverse knowledge base may attract inventive activities which are more complex and multidisciplinary. As a result we propose that inter-industry spillovers and diversity externalities should be taken into account in this new context.

We also propose to consider the level and quality of the science base in attracting early-stage research and innovation in emerging technologies. Scientific activity is increasing in several rapidly developing economies, particularly in China and India. In China, for example, R&D intensity (R&D expenditures as a percentage of the gross domestic product) increased from 0.69 in 1998 to 1.34 in 2005, rising from about 32 percent to almost 60% of the average for developed (OCED) countries over this period (National Science Board 2002 & 2008). A significant share of these additional R&D resources has been channeled into new fields such as nanotechnology, where China is now the second largest national producer of scientific publications after the United States (Kostoff et al. 2007). Although still below the level of the US, the aggregated quality of China's nanotechnology research, as measured by citations to it, is increasing (Zucker and Darby, 2005; Youtie et al. 2008). Perhaps more important than aggregates, several top Chinese universities and units of the Chinese Academy of Sciences have emerged as leading centers of nanotechnology research (Tang and Shapira 2008).

The emerging field of nanotechnology is the focus of our exploratory analysis. Nanotechnology involves manipulating molecular-sized materials to create new products and process with novel features due to their nanoscale properties and is widely anticipated as one of the next drivers of technology-based business and economic growth around the world (Lux Research, 2004).[2] We believe that this field is an appropriate one

[2] A distinction should be made between the terms *nanoscience* and *nanotechnology*. Nanoscience refers to the search for fundamental new knowledge to understand structures, materials, and components at the scale of roughly 1-100 nanometers (nm). Nanotechnology is a broader concept that refers to the application of that knowledge to design and use. More formally, we can say that nanotechnology consists of the creation of systems, devices, structures and materials at the 1 – 100 nanometer scale with novel properties and functions because of their small size (PCAST, 2005). Whereas the growth of codified knowledge in nanoscience can be captured by examination of scientific publication, for nanotechnology the intrinsic characteristics of patents (novelty, non-obviousness, and usefulness) make them appropriate for analyzing the development and application potential of this emerging technology.

to test our hypotheses. Although there is debate as to the direction and relationships of development in nanotechnology (see, for example, Bonaccorsi and Thoma 2007), several studies have argued that nanotechnology is a convergent scientific domain that uses diverse knowledge bases and enables technological changes in other fields.

Reports by Rocco and Bainbridge (2003) and Nordmann (2004), find that nanotechnology covers multiple disciplines, including engineering, biology, chemistry, materials science and computing. Avenel et al. (2007) also demonstrate, with the use of Herdfindahl indexes, how the breadth of corporate publications and patents in nanotechnology over the period 1993-2003 spread over a large number of fields, regardless of firm size. It is possible that the multidisciplinary nature of nanotechnology will result in locational patterns that differ from those found for prior technologies which are more specialized. We suggest that the emerging complexity and convergence of nanotechnology may induce corporate research and innovation in this field to cluster in certain locations which possess a breadth of research capabilities as corporations recognize the importance over time of this domain.

2.1 Empirical model

Building on our review of prior theoretical and empirical findings, we suggest that the nature and development of MNC inventive activities is influenced by three set of factors: characteristics of home-country and host-country innovation systems, MNCs strategic decisions on where, how and what to locate abroad, and the role of subsidiaries' development. To understand how these factors affect MNCs location decisions, we propose to make a distinction between country of origin of MNCs, while considering a set of innovation characteristics of host-countries, MNCs and subsidiaries.[3] In addition,

[3] Instead of limiting the analysis to a particular country of origin of MNCs, another methodological solution could be to use dummy variables for each country of origin of MNCs. However, country comparability is problematic because there are country biases in the use of different patent offices (Schmoch, 2007). As a result, our empirical model focuses on MNCs from a specific country.

our contribution emphasizes the need to consider specific evolving elements of the technology developed abroad and the role of scientific and technological spillovers within disciplines. In particular we postulate that in nanotechnology the multidisciplinary nature of the field and the quality of related scientific codified knowledge may affect MNCs decisions as well. We therefore set up to estimate the following empirical model for a group of US-based MNCs,

$$P_{ijt} = b_1 x_{1jt-1} + b_2 x_{2jt-1} + \Sigma_k b_k x_{kjt-1} + \Sigma_n b_n x_{nit-1} + e_{ijt} \qquad [1]$$

where P_{ijt} is the number of patents invented in a host country *j* by a given firm *i* during *t*,[4] x_{1jt-1} stands for technological diversity of host county *j* during time *t-1* and x_{2jt-1} is scientific excellence of host county *j* during time *t-1*. x_{kjt-1} is a vector of host country characteristics that we control for, including market size and overall scientific strength, x_{nit-1}, is a vector of MNCs and subsidiaries' characteristics, including past inventive experience in host countries, firm's capacity for patenting R&D and pre-sample patents in nanotechnology. e_{ijt} stands for random error terms.[5]

Explanatory variables of interest

Technological diversity in nanotechnology of host countries

Technological diversity captures whether the breadth of nanotechnology patents invented in host countries is spread over a large number of technology domains or whether it

[4] In total our sample size consists of 625 observations. These observations correspond to the total number of US assignees multiplied the total number of host countries with one patent invented totally or partially abroad and assigned to those corporations. We find that the US companies in our sample invent in a total of 25 host countries. Each observation is therefore unique for each company and each location.

[5] The use of patents as indicator of inventive activity has long been emphasized in the literature (see Griliches, 1990, for a review). Despite the technical difficulties associated with patents and the fact that not all inventions are patentable, patent documents are rich information sources that can be used to study, among other topics, the geographic distribution of particular inventions. By limiting the analysis to a specific domain, we reduce potential differences that could emerge between fields and industries with different propensities to patent (Arundel and. Kabla, 1998).

remains concentrated in few fields. To compute this measure we propose to use the reciprocal of the Gini, computed as,

$$G_i = \frac{2\sum_{j=1}^{n-1} CP_{ij}}{(n-1)\ (\sum_{j=1}^{n} P_{ij})}$$

where *n* is the total number of technology domains in which a country is patenting, *j* is the technological domain defined by patent class, CP_{ij} is the cumulative sum of patents by county *i* in technology field *j*, ranged in increasing order, and P_{ij} is the number of patents in each technological class.[6] This index varies between 0 and 1, with larger values indicating greater diversity. It is appropriate in our case because, as posed by van Zeebroeck et al. (2006), the Gini index is the most sensitive indicator to the presence of a large number of small patent classes.

In the industrial organization literature, the scope of a patent has been related with the economic value of a patent (Lerner 1994). The more general the research content of a patent, the greater the ability of the assignee to secure markets in different fields and the higher the probability to be cited by patents in different technology classes. In the economic geography literature, it has been suggested that the patent scope is also a good proxy to measure the presence of inter-industry spillovers and diversity externalities (Cantwell and Piscitello 2005). We interpret a significant and positive coefficient of our measure of technological diversity as a signal of the presence of these positive externalities.

[6] Patent scopes indexes are generally computed using the International Patent Classification (IPC) class in which a patent office assigns a patent (see, for example, Cassiman et al. 2006). As explained below, we use this classification at the three-digit level.

Scientific excellence in nanotechnology of host countries

To measure to what extent host countries' nanotechnology scientific excellence affects the conduct of invention activities of foreign firms, we propose to look at the nanotechnology publications of host countries and the number of times those host country publications have been cited. Accordingly, a citation index is defined. $C_j=(\sum x_{kj*} c_k / X_j)$, where c_k is the number of times a publication is cited, x_{kj} is the number of publications cited c_k times in each host country j, and X is the total number of publications originating in the country.

Country-level control variables

Market size of host countries

The impact of host country market size on the conduct of R&D has long been discussed in the literature (see, for example, Vernon 1966, 1979; Mansfield et al. 1979). However, empirical evidence on this issue remains ambiguous. Belderbos (2006), for example, finds that the market size of a host country increases the expected number of patents of an affiliate by about 25%, but when controlling for an affiliate's location in Asian regions, market size variables become negative. Ambiguous results are also found in Almeida and Phene's (2004) analysis of foreign subsidiaries of US semiconductor firms.

By contrast, Kumar (2001) in a cross-country comparison of Japanese and US R&D finds a positive impact of market size on the level of R&D expenditures of affiliates. Similarly, Odagiri and Yasuda (1996), in their examination of R&D activities by Japanese multinationals abroad, find that industries with larger local sales are more likely to engage in overseas R&D. Cantwell and Piscitello's (2005) regional analysis of inter-industry spillovers and diversification externalities in Europe finds a positive (but weak) impact of regional Gross Domestic Product (GDP) on the number of patents awarded to subsidiaries. To control for the influence of market size and purchasing power, we use the Gross Domestic Product and the Gross Domestic Product per capita of host countries.

S&T capabilities of host countries

Several surveys show that scientific and technological capabilities of host countries are an important factor in explaining R&D activities of MNCs (see, for example, Florida 1997; Edler et al. 2002; EIU 2004; and Thursby and Thursby 2007). Similar results are found in econometric studies. Kuemmerle (1999), for example, finds that world-wide pharmaceuticals and electronics MNCs with R&D facilities in foreign countries are more likely to develop sophisticated R&D when the host country has a relative advantage in terms of R&D intensity, scientific achievements and quality of human resources. Kumar (2001), based on data from US and Japanese affiliates, finds that national technological effort, measured by R&D over GNP, attracts a greater proportion of the R&D performed in affiliates. This pattern holds for both US and Japanese affiliates.

Feinberg and Gupta (2004), using data for US-owned affiliates in R&D-intensive industries, find that the probability of conducting R&D in foreign locations is positively associated with the total R&D expenditure by other firms (including both US affiliates and non-US affiliates) from the same industry firms within the host country. Ito and Wakasugi (2007) find that Japanese affiliates are more likely to locate R&D labs in countries that have more researchers. Results are less clear in Almeida and Phene (2004). Using a sample of US multinational enterprises engaged in the semiconductor industry, they find that the technological strength of host countries has a significant and positive effect on patent counts when subsidiaries have previous experience in patenting. But the relationship does not hold when subsidiaries have one or fewer patents in the previous five years.

Todo and Miyamoto (2002), for the case of Indonesia find that knowledge diffusion from multinational enterprises requires foreign or domestic efforts in R&D and human resource development. Fernández-Ribas, Shapira and Youtie (2006) for Malaysia find that the average level of domestic R&D expenditures explain to a great extent the probability that a MNC engages in innovation activities in all the parts of the innovation value chain , including R&D, design and marketing activities, in the host country. Cantwell and Piscitello (2005) find evidence of the effects of regional intra- and inter-industry spillovers on the probability that a US affiliate engages in R&D. To control for the influence of overall scientific strength of host countries, we propose to include a continuous variable on the number of scientific and technical publications (in all fields of science) originating in each host country.

Firm-level control variables

Firm's experience in host countries

Several contributions in the management literature pinpoint the role of subsidiary development in the expansion of innovation activities abroad (see for example, Birkinshaw et al. 1998; Subramaniam and Venkatraman 2001; Rugman and Verbeke 2001; Furu 2001). These authors find that subsidiary-specific characteristics, such as size, age or managers' leadership behavior, influence the type of innovation activities that affiliates perform. A subsidiary's ability to overcome the "liability of foreignness" is another related topic mentioned in this regard (Zaheer and Mosakowski 1997; Sofka 2006). MNCs with operations in foreign locations may encounter institutional and cultural barriers that increase costs and reduce profitability of R&D projects (Bakerma et al. 1996). Managers' ability to overcome these barriers is a crucial point that may help to explain why some subsidiaries are doing more innovation than others. While we are not able to control for all these elements, we can test whether a firm's experience in a host country positively affects the number of subsequent patents developed in that country. To test this hypothesis we compute the number of nanotechnology patents invented in a host country during prior period.

Incumbent advantages

Our second firm-level control variable refers to firms' incumbent role in nanotechnology. It is plausible to propose that prior experience in the formal process of patenting results in the development of tacit knowledge and capability in the field which, in turn, can be applied to subsequent research and innovation activities. As pointed out by Rothaermel and Thursby (2007), incumbent firms may have an initial competitive advantage due to their higher level of tacit knowledge in the field. We therefore include in our analysis a variable for the number of pre-sample nanotechnology patents assigned to a firm.

Firm technological capabilities

Finally, we control for the scale of a firm's innovation capabilities by using total USPTO patents awarded to a sample firm in all technological fields. Although corporate R&D expenditures could be used, this raises some concerns. On the one hand, it is difficult to find an accurate measure of R&D investment that captures all research activities done by a major corporation and its often many affiliates. On the other, according to systemic and evolutionary models, R&D is just one input to the innovation process. Hence, instead of using a firm's level of R&D, we use a firm's patentable output as a measure of technological capability.

3. Data sources and data characteristics

The model explained in previous section is estimated using a set of 25 US-based firms with the greatest number of nanotechnology-combined patents.[7] This includes patents granted by the US Patent Office (USPTO) and by the European Patent Office (EPO), as well as patent applications filed under the Patent Cooperation Treaty (PCT) at the World Intellectual Property Organization (WIPO). By selecting patent data from more than one patent office we seek to have a more representative global picture of the inventive activities of US firms. In total, 3742 patents are assigned to these companies and their subsidiaries during 1997-2006.

To obtain this data, we searched the global database of nanotechnology patents developed by the Program in Research and Innovation Systems Assessment (CNS-ASU Center for Nanotechnology in Society) at Georgia Tech. This database contains patent abstracts for the period 1990-2006 (mid-year) selected using the nanotechnology search term described in Porter et al. (2007). The dataset includes awarded patents from USPTO, EPO, JPO and German, UK, and French patent offices, patent application filings at WIPO, and patents from an INPADOC search of 72 issuing countries. In order to avoid duplicate patents for the same invention, this database generates one patent per patent family.[8]

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[7] These companies have 50 or more nanotechnology combined patents during the period under study. By industry category (using the Dow Jones Industry Classification Benchmark), the companies are: automobiles and parts: Ford Motor Company; chemicals: Dow Chemical Company, EI Du Pont de Nemours, Exxon Mobil Chemical, PPG Industries, Rohm & Haas; computer hardware: Hewlett-Packard, International Business Machines, Lucent Technologies, Seagate Technology; electronic office equipment: Xerox; general industrials: 3M, General Electric, Honeywell International; household goods: Procter & Gamble; leisure goods: Eastman Kodak; materials: Hyperion Catalysis[*]; personal goods: Kimberly-Clark; semiconductors: Advanced Micro Devices, Applied Materials, Intel, Micron Technology, Texas Instruments; telecommunications equipment: Corning Incorporated, Motorola. [*]Although not a large MNC, this is an internationally-active company in the top 25 of all US nanotechnology patenting companies. We have thus included it in the analysis.

[8] Initially we considered all patent offices included in the dataset. However, we found that, except for USPTO, EPO and WIPO, other patent offices did not have complete information on the location of inventor. As a result, we only used awarded patents by USPTO and EPO and granted WIPO PCTs. As we are not comparing patent activities of companies from different countries, the use of different patent offices is appropriate and desirable.

To develop an accurate picture of the invention activities carried out abroad by private corporations, our analysis is based on consolidated group companies of the ultimate parent company. Companies are assigned to the location of the corporation's registered office. Consolidated majority-owned subsidiaries are obtained from several corporate directories, including Dun and Bradstreet, Who Owns Whom, Mergent, and 10-K reports submitted to the US Securities and Exchange Commission (SEC). Mergers and Acquisitions (M&A) after 2005 and joint-ventures by corporate firms are not considered. Individual patents were then unified into corporate families.[9] Information on the location of the inventor was then extracted from the patent records assigned to corporate groups. Finally, inventor cities were assigned to countries and host countries selected as having at least one patent (totally or partially) assigned.[10] [11]

We complement this data with information extracted from four other different sources. The nanotechnology publications used to compute the citation index come from the Georgia Tech nanotechnology publications database. This database was constructed using the methods described in Porter et al. (2007). It contains nanotechnology publication records for the period 1990-2006 (mid-year). Scientific and technical publications (in all fields) to measure host country overall scientific strength were obtained from the Thomson ISI (Web of Science) Science Citation Index. Market-size variables were extracted through the World Bank macroeconomic database. To obtain firm's level of overall technology strength we did a search at USPTO of consolidated names of companies.

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[9] An extensive manual checking was undertaken to unify name variance of assignee firms and their subsidiaries. As noted by Griliches (1990), patent offices do not employ consistent company codes for each corporation.

[10] The geographic address of the inventor is a more desirable indicator of the site of the inventive process than the location of the assignee, because the assignee location may be biased towards head-office administrative locations (Jaffe, Trajtenberg and Henderson 2002).

[11] The main difficulty with the inventor location is that regional codes may correspond to country codes. For example, country/state code "CA" sometimes refers to Canada and other times to California, "IL" to Israel or Illinois, "IN" to India or Indiana, and "ID" to Indonesia or Idaho. To avoid misleading results regarding inventor cities and countries, inventor cities were assigned manually to correct countries/states.

Table 1 provides a detailed description of variables employed in our analysis. The dependent variable of the model refers to the number of patents invented (totally or partially) in a host country during 2002 and 2006 assigned to a sample firm. The technology diversity index is based on three-digit level IPC classes for 1997-2001. The citation index is measured using nanotechnology publications originating in a host country during 1997-2001, and times cited by 2006. Gross Domestic Product and Gross Domestic Product per capita are averaged for 1997-2001. These figures are expressed in logs of US dollars converted at purchasing power parity (PPP) exchange rates (current international dollars). S&T publications originating in each host country are also averaged for 1997-01 and expressed in logs. Firms' incumbent role in the field of nanotechnology is computed as the number of nanotechnology patents assigned to a sample firm during 1992-1996. Firms' experience in developing invention in a host country is measured as the total number of patents invented in a host country by a firm during the period 1997-2001. Firm size is proxied by the average number of USPTO patents assigned to a firm during 1997-2001.

3.1 Data characteristics

Our dataset represents about 13% of the total number of nanotechnology patents contained in the USPTO, EPO and WIPO dataset. As can be seen in Figure 1, the gap between sample firms and patents assigned to other organizations increases over our study period. This observation corroborates that large incumbent firms played a critical role in the early development of nanotechnology, taking associated risks and investing resources, and as a result lead early patenting in the field. However, as the field developed, incumbent firms tended to lose the temporary monopoly that they have had in initial stages of nanotechnology.

Overall, we observe that the total number of patents co-invented abroad by these companies more than double during 1997-2001 and 2002-2006. However, when compared to the total number of patents invented at home, we observe that the percentage of patents co-invented abroad (totally or partially) drops from 17% in 1997-01 to 13% in 2002-2006 (table 2). These results are in line with Patel and Pavitt's (1991) predictions about the small proportion of R&D activities performed abroad by US large firms. They also corroborate the idea posed by Cantwell (1995) that US firms tend to internationalize a small proportion of their R&D activities, particularly for those technologies which have a high strategic importance and are multidisciplinary by nature. The superiority of US firms and universities in nanotechnology may be suggesting that MNCs are indeed globalizing part or their R&D process, but the growth of the number of patents invented at home is more important.

Invention takes place primarily in highly industrialized countries such as Canada, Germany, France, UK, Belgium or Japan (see Figure 2). These countries attract more than two-thirds of the invention activities developed abroad by US companies. When comparing dynamics for five year periods 1997-2001 and 2002-2006, several interesting facts emerge. First, we observe the inclusion of new host countries, such as India, South Korea, Malaysia, Singapore, Norway, Portugal and Turkey in the most recent period. Although these new places do not have large numbers of patent counts, this development is indicating a dispersion trend. Second, the proportion of invention activities developed by US companies in Canada, Germany, UK, France, Belgium and Italy decreases, while invention taking place in other developed economies, such as Japan, the Netherlands and Switzerland, grows.

Table 3 reports descriptive statistics for sample firms. Geographic dispersion of the inventive process varies across companies. For the majority of companies, inventions developed abroad are invented in four or five different countries. However, there are some exceptions. General Electric (GE) for example is the most widely dispersed company with patents co-invented in 13 different countries, International Business Machines (IBM) and Procter and Gamble (PG) are also among quite geographically dispersed companies. Xerox has the largest number of patents developed abroad during 1997-2001 and 2002-2006 (51 and 78, respectively). A majority of these patents are co-invented in Canada. This is not very surprising, given the fact that Xerox has an R&D facility "Xerox Research Center Canada" since 1974, which has over 1000 patents (10% in nanotechnology). Heterogeneity across countries is also present in terms of technological diversity and patent quality (see Figures 3 and 4).

Larger host countries such as Germany, France and Great Britain are the most diversified in terms of different nanotechnology patent classes, while developing countries are the least diversified. The reciprocal of the Gini coefficient takes values larger than 0.5 for the first group of countries, and less than 0.02 for the second group. Publication quality is lead by the Netherlands Israel, Canada, Ireland, Germany, Great Britain, Belgium, and Sweden, which have on average more than 15 publication citations in nanotechnology per year, while countries such as, Russia and Thailand have less than 7 citations per year.

4. Estimation method and econometric results

Empirical models with non-negative count dependent variables are commonly estimated using the Poisson distribution (Wooldridge 2002). However, our response variable exhibits a series of features that may restrain the use of the Poisson model. First, our dependent variable is skewed-distributed. Some firms have a dispersed location pattern while others just invent in one or two host countries. As a result, there are some host countries with a high number of patents invented totally or partially by US companies, while other host countries have few of these inventions. The Poisson model is less adequate in such cases, because it assumes equi-disperison between the conditional variance of the count variable and its conditional mean. In this case, it is more efficient to use negative binomial models, which allow for overdispersion by including a parameter alpha into the Poisson distribution.

Second, as our dependent variable is set to have all possible firm-country combinations, it contains a large number of zeros. To deal with this issue, we consider models which differ from the standard negative binomial by considering different distributions for the zero and non-zero counts. Lambert (1992) and Greene (1994) provide an extensive overview of the characteristics of these models. Basically, these models estimate the zero count regime using the cumulative logistic distribution (logit model) or the cumulative normal probability (probit model), and the non-zero counts using a maximum likelihood negative binomial model.

4.1 Econometric results

Tables 4 and 5 show econometric results, using five different right-hand specifications. The first model includes host country control variables as well as the firm's experience in the nanotechnology field and in patentable R&D. We then estimate three specifications: one including our measure of technological diversity, a second with the publication quality measure, and a third including both measures. Finally, we incorporate a variable for a firm's experience in developing inventions in host countries. These specifications are initially estimated using a negative binomial maximum-likelihood model. As can be seen in table 6, a likelihood ratio test of presence of overdispersion in our dependent variable confirms that *alpha* (the overdispersion parameter) is significantly different from zero, suggesting that the negative binomial is preferred to the Poison regression. The Vuong test suggests that we can not reject the null hypothesis that the zero inflated binomial model is a better choice than the negative binomial model. The value of the

Vuong test also indicates that the zero-inflated negative binomial is favored against a zero-inflated Poisson model in the fifth specification.

Our estimations confirm previous evidence on the positive impact of overall scientific strength of host countries. All of our five specifications confirm that countries with more S&T capabilities attract more inventive activities by US MNCs. Market size, measured by the lagged value of GDP and GDP per capita, has a more erratic pattern. Not surprisingly, larger firms, with more patentable R&D activities, tend to do more innovative activities abroad. Firm's previous experience in nanotechnology also increases the expected number of patents developed in foreign countries. Experience in a host country is also positively related with the expected number of patents developed in a host country.

More interestingly, our measure of technological diversity turns to be quite important in explaining the inventive process of US MNCs in foreign locations. We find that countries which have patent activities in broader patent classes are attracting more R&D from US companies. This result seems to corroborate the importance of scope economies in the production of knowledge and the importance of diversity externalities in the globalization of R&D. It may be indicating that interdisciplinarity in a new field stimulates productivity. On the other hand, publication quality also induces a positive change in the probability of inventing in foreign locations, but it is not always significant.

Overall, our estimated models suggests that host countries with more scientific resources and more technological diversity in the field of nanotechnology are more likely to attract invention activities by US firms. These are primarily advanced developed economies: at least in the case of MNC patentable nanotechnology R&D, there is not a wholesale shift to emerging developing countries. Regarding the characterization of firms, estimations suggest that firms with more patentable R&D and more experienced in the field of nanotechnology and in developing nanotechnology activities in host countries are also more likely to do invention in host countries. We interpret these results as suggesting that host country nanotechnology capabilities are important to attract innovative activities of US MNCs, but as the interdisciplinary and convergent nature of nanotechnology evolves, access to a broadly diversified knowledge base becomes important, which increases the relative attractiveness of home locations.

5. Conclusions

This study investigates how technological complexity and the convergent character of an emerging technology influences innovation location decisions by US MNCs. We suggest that as fields evolve and S&T capabilities spread over a larger number of countries, new explanatory factors should be explored in order to understand firms' complex choices about where to locate invention activities. In particular, we anticipate that a host country's technological diversity and its scientific excellence in the field may be two important factors that explain inward research activities from foreign companies.

To investigate these hypotheses we selected the most technologically active US-owned firms in the field of nanotechnology during the ten year period, 1997-2006, and studied how foreign country diverse technological capabilities and scientific performance affect the probability of attracting invention activities by these leading US nanotechnology R&D companies. In order to deal with potential time issues, we set up an appropriate lagged econometric model on the number of patents invented in different host countries. Our model also controls for other country-level characteristics, such as market size and overall scientific strength. From the firm side, we control for previous experience in developing innovation activities abroad, the ability to commercialize R&D, and experience in the development of nanotechnology activities.

Our results point to the relative importance of having a diversified technological base. We find that technological breadth, measured by the reciprocal of the Gini coefficient, is a strong predictor of the number of patents co-invented abroad by US-companies. Our measure of scientific excellence is positively correlated with US firm's patenting activities, but is not significant in all specifications. The positive impact of host country overall scientific strength is confirmed. These results seem to be consistent with the idea that R&D location decisions are driven by firms' desire to access multidisciplinary knowledge bases and globally competitive S&T. Our findings regarding the ambiguous role of market size are consistent with recent studies on patenting (Belderbos 2006; Almeida and Phene 2004). At the firm level, we find that previous experience in host countries, technological strength in the field and overall strength of patentable R&D positively impact a firm's capacity to develop foreign R&D activities. These results may suggest that inventing abroad is a path dependent learning process, and that tacit knowledge in the field is important.

These results have several implications for both governments and firms. We find that the attraction of foreign R&D in the field of nanotechnology is driven by a combination of factors. Particularly important is the ability of local innovation systems to adapt to the increasing interdisciplinarity nature of the field. Having S&T capabilities also helps to attract foreign R&D, but as scientific and technological competencies spread globally, the quality of science may be another distinguishing factor that attracts foreign investment in R&D as well. This emphasizes the importance of having flexible horizontal policies to stimulate knowledge flows across disciplines and to avoid lock-in situations.

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Table 1. Definition of variables and related hypothesis

Variable	Description/Hypothesis
Nanotechnology patents invented abroad	Number of patents invented abroad (totally or partially) assigned to a sample firm during 2002-2006. Dependent variable of the model.
Technological diversity in nanotechnology	Reciprocal of the Gini index. Based on three-digit IPC patent classes during 1997-2001. Attracts complex multidisciplinary inventive activities in nanotechnology.
Scientific quality in nanotechnology	Weighed number of citations received by 2006 of nanotechnology publications originating in a host county during 1997-2001. Attracts inventive activities in nanotechnology which have a high science based component.
Market size	Average GDP 1997-2001 (in logs) and average GDP per capita 1997-01 (in logs). Attracts inventing activities in nanotechnology because of high demand for applications and products.
Overall scientific strength	Average number of S&T publications originating in a host country during 1997-2001 (in logs). Attracts complex multidisciplinary inventive activities in nanotechnology.
Previous nanotechnology patents invented abroad	Number of nanotechnology patents invented abroad (totally or partially) assigned to a sample firm in 1997-2001. Firm's previous experience in host countries may affect current inventive activities in host countries.
Pre-sample nan otechnology patents	Number of nanotechnology patents assigned to a sample firm during 1992-1996. Previous experience in nanotechnology positively affects the capacity to develop nanotechnology abroad.
Overall firm technological strength	Average number of USPTO patents assigned to a sample firm during 1997-2001. Strength of patentable R&D (proxy for R&D expenditures) positively affects the capacity to develop technology abroad (including nanotechnology).

Table 2. USPTO/EPO/WIPO nano patents awarded to top US firms, developed at home and abroad.

Variable	1997-2001	2002-2006
Total number of patents	1187	2555
Patents co-invented abroad	182 (17%)	335 (13%)
Patents totally invented abroad	117 (10%)	206(8%)

Note: Percentages are relative to total number of patents with complete information about inventor locations. We did an extensive analysis of the distribution of missing cases, and arrived to the conclusion there were no systematic differences across patent offices. Only1%-2% of patents have missing information on inventor city.

Table 3. Descriptive Statistics

Variable	Mean	Std. Dev.	Min	Max
Patents invented abroad *t*	0.59	3.56	0	78
Patents invented abroad *t*-1	0.33	2.32	0	51
Technological diversity *t*-1	0.25	0.19	0	0.73
Scientific excellence *t*-1	13.27	4.24	7.70	23.04
Log GDP *t*-1	13.10	1.25	10.29	15.34
Log GDP per capita *t*-1	9.63	0.72	7.74	10.41
Log S&T publications *t*-1	9.51	1.17	6.76	11.27
Pre-sample patents *t*-2	19.20	18.13	0	68
Firm's technological strength *t*-1	5.57	1.85	0	7.91

Note: Observations = 625

Table 4. Results Poisson and negative binomial (nb) specification predicting number of patents invented in a host country by US MNCs

	Poisson	nb	Poisson	nb	Poisson	nb	Poisson	nb	Poisson	nb
GDP *t*-1	-0.33***	-0.13	-0.24***	-0.06	0.23***	0.13	0.28***	0.12	-0.09	0.08
	(0.08)	(0.23)	(0.09)	(0.23)	(0.11)	(0.28)	(0.12)	(0.27)	(0.13)	(0.24)
GDP per capita *t*-1	0.16	0.27	0.10	0.08	-0.23	0.12	-0.24	0.001	-0.29*	-0.15
	(0.14)	(0.27)	(0.15)	(0.28)	(0.15)	(0.28)	(0.15)	(0.29)	(0.16)	(0.25)
Scientific strength *t*-1	1.34***	1.11***	1.03***	0.70**	0.82***	0.79**	0.64***	0.54*	0.69***	0.47*
	(0.13)	(0.28)	(0.16)	(0.34)	0.15)	(0.33)	(0.19)	(0.36)	(0.20)	(0.32)
Firm's pre-sample patents *t*-2	0.02***	0.02***	0.02***	0.03***	0.02***	0.02**	0.02***	0.02***	0.003	0.01*
	(0.002)	(0.0083)	(0.003)	(0.01)	(0.002)	(0.01)	(0.003)	(0.01)	(0.003)	(0.01)
Firm's patentable R&D *t*-1	0.22***	0.35***	0.22***	0.34***	0.22***	0.34***	0.22***	0.34***	0.34***	0.29***
	(0.05)	(0.11)	(0.05)	(0.11)	(0.05)	(0.11)	(0.05)	(0.11)	(0.06)	(0.10)
Technological diversity *t*-1			1.31	2.52**			0.73***	2.11	2.15***	1.44*
			(0.40)	(1.32)			(0.42)	(1.33)	(0.48)	(1.11)
Publication quality *t*-1					0.20***	0.10*	0.20***	0.07*	0.04*	0.06
					(0.02)	(0.06)	(0.03)	(0.06)	(0.03)	(0.05)
Experience in host country *t*-1									0.09***	0.33***
									(0.00)	(0.10)
Constant	-13.11***	-15.31***	-10.99***	-11.12***	-14.58***	-15.54***	-13.42***	-11.96***	-7.15***	-8.94***
	(1.45)	(3.6)	(1.64)	4.04	(1.48)	(3.51)	(1.65)	(4.06)	(1.92)	(3.42)
LR chi2	528.27***	85.31***	538.77***	89.04***	592.02***	87.93***	594.93***	90.51***	-569.78***	127.33***
Log likelihood	-857.85	-413.72	-852.60	-411.85	-825.97	-412.40	-824.52	-411.12	1104.4	-392.71
Pseudo R2	0.2354	0.0935	0.2401	0.0976	0.2638	0.0963	0.2651	0.0992	0.49	0.1395

Note: Standard deviation in parenthesis. * p<0.10; **p<0.05; ***p<0.01. Coefficients reported.

Table 5. Results negative binomial (nb) and zero-inflated negative binomial (zinb) predicting number of patents invented in a host country by US MNCs

	(1)		(2)		(3)		(4)		(5)	
	nb	zinb	nb	zinb	nb	zinb	nb	zinb	nb	zinb
GDP *t*-1	-0.03 (0.05)	-0.02 (0.06)	-0.01 (0.05)	0.02 (0.07)	0.03 (0.06)	0.06 (0.09)	0.03 (0.06)	0.06 (0.08)	0.02 (0.05)	0.01 (0.08)
GDP per capita *t*-1	0.06 (0.06)	0.08 (0.09)	0.02 (0.06)	0.03 (0.08)	0.03 (0.06)	0.04 (0.09)	0.003 (0.06)	0.003 (0.09)	-0.03 (0.05)	-0.05 (0.10)
Scientific strength *t*-1	0.25*** (0.06)	0.27*** (0.08)	0.16** (0.07)	0.13** (0.09)	0.18** (0.07)	0.19** (0.09)	0.12** (0.08)	0.08 (0.10)	0.09* (0.06)	0.11* (0.10)
Firm's pre-sample patents *t*-2	0.01*** (0.002)	0.01** (0.004)	0.01*** (0.002)	0.01** (0.002)	0.005** (0.002)	0.005** (0.002)	0.01** (0.002)	0.01** (0.002)	0.002* (0.002)	0.002* (0.002)
Firm's patentable R&D *t*-1	0.08*** (0.02)	0.08** (0.03)	0.08*** (0.02)	0.08*** (0.03)	0.08*** (0.02)	0.08*** (0.03)	0.08*** (0.02)	0.08*** (0.03)	0.06*** (0.02)	0.09*** (0.04)
Technological diversity *t*-1			0.57* (0.31)	0.91** (0.45)			0.47* (0.31)	0.87* (0.48)	0.28 (0.22)	0.75* (0.42)
Publication quality *t*-1					0.02* (0.01)	0.03* (0.02)	0.02 (0.01)	0.02 (0.01)	0.02 (0.01)	0.01 (0.02)
Experience in host country *t*-1									0.06*** (0.02)	0.46** (0.24)
Log Likelihood	-413.72	-409.62	-411.85	-406.60	-412.41	-409.61	-411.12	-404.22	-392.71	-368.52
Chi-Square test	85.31***	32.40***	89.04***	31.91***	87.93***	32.40***	90.51***	35.98***	127.3***	64.98***

Note: Standard deviation in parenthesis. * $p<0.10$; ** $p<0.05$; *** $p<0.01$. Marginal effects reported

Table 6 Results Overdispersion and Vuong Tests

Specification	(1)	(2)	(3)	(4)	(5)
Overdispersion test[a]	888.3***	881.5***	827.1***	826.8***	354.1***
Vuong Test[b]	1.55*	1.59*	1.87**	1.94**	3.19 ***

Note: [a] The hypothesis being tested is that the overdispersion parameter (alpha) is zero. A likelihood ratio test indicates that we can not accept the null hypothesis that the negative binomial distribution is equivalent to the Poisson distribution. [b]The null hypothesis is that a zero-inflated negative binomial fits better the data than an ordinary negative binomial. The test indicates that we can accept this hypothesis.

Figure 1. Annual number of USPTO/EPO/WIPO nano patents granted to all organizations vs granted to the most technologically-active US firms

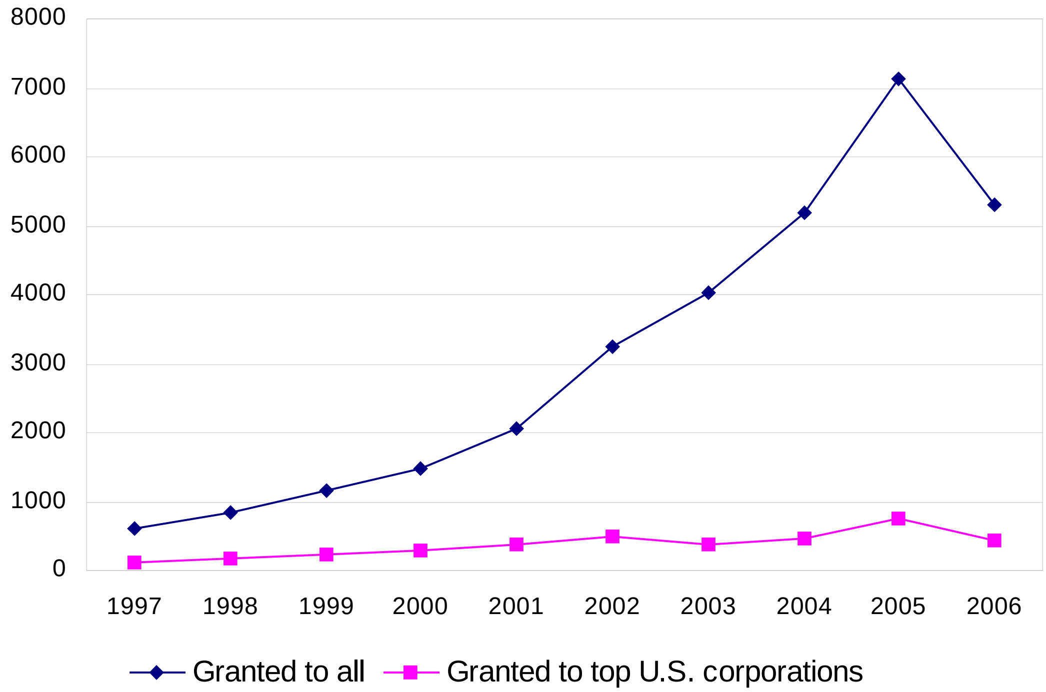


Figure 2. Location patterns of inventive activity in nano by top U.S. companies, host countries.

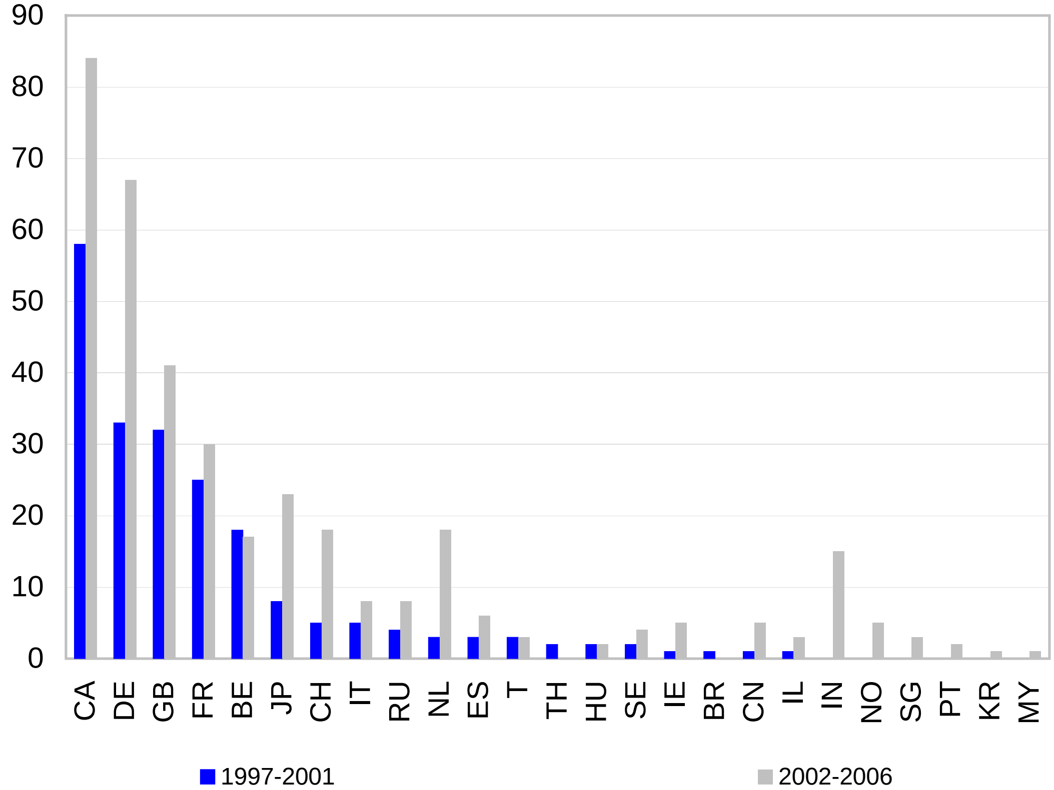
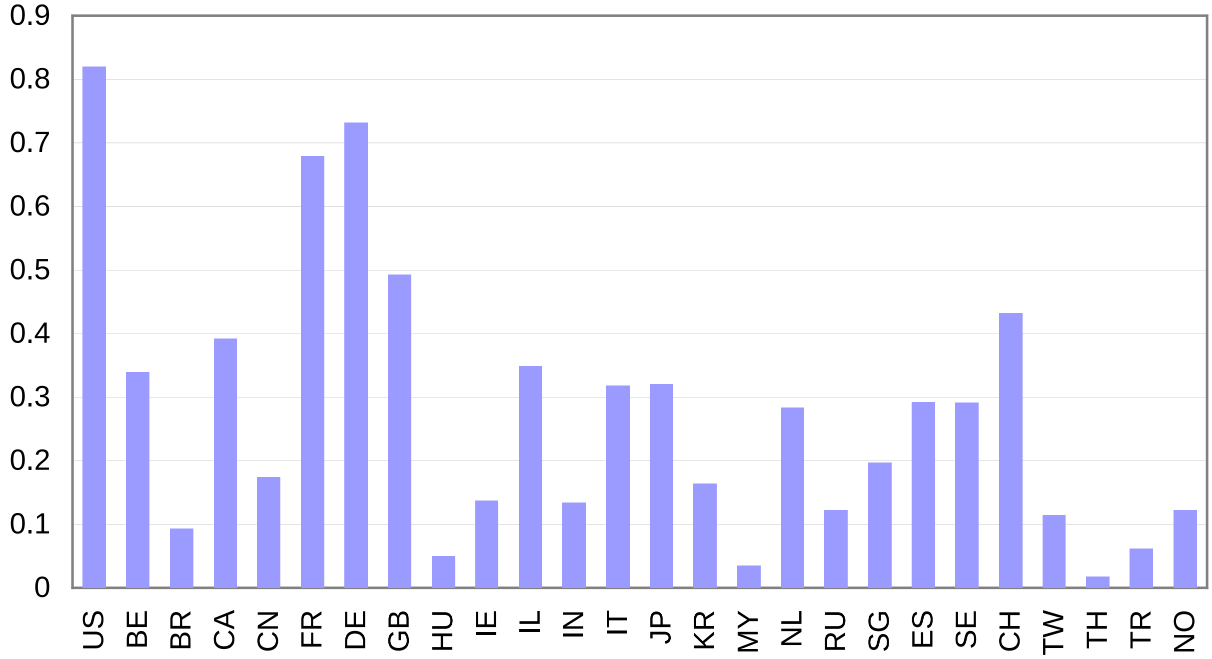
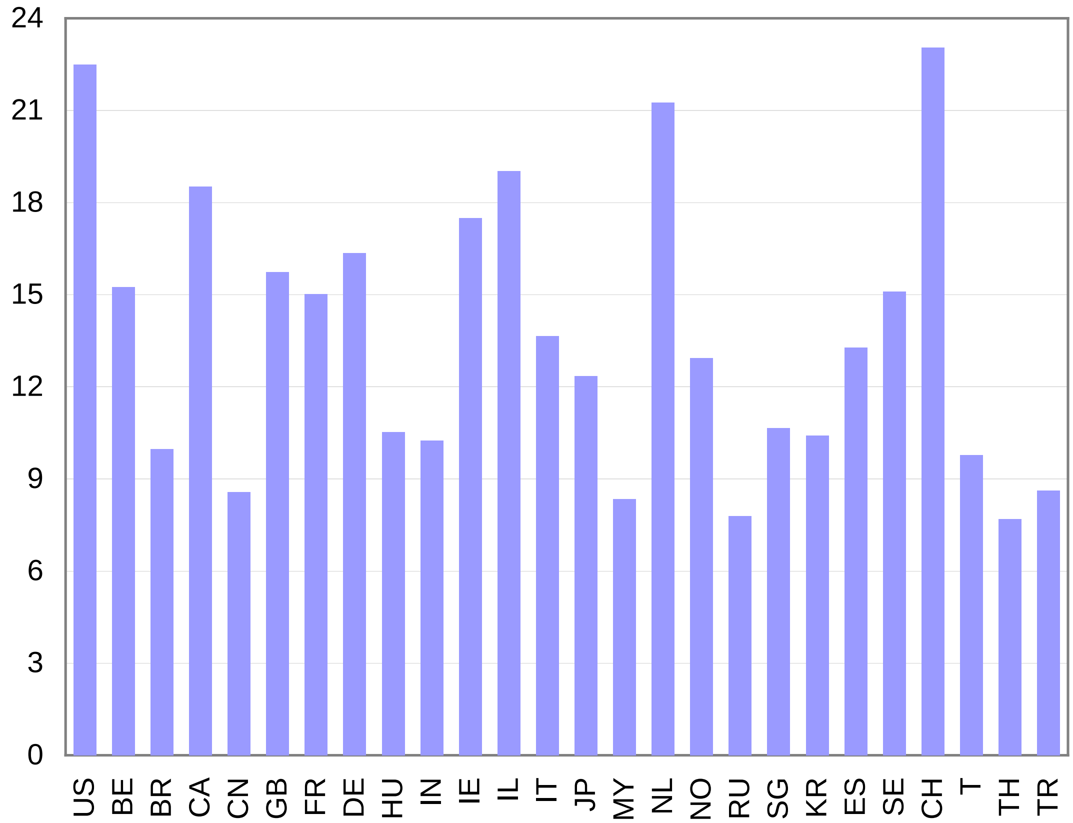


Figure 3. Technological Diversity Index 1997-2001



Note: See country codes in the appendix

Figure 4. Citation Index 1997-2001



Note: See country codes in the appendix

Appendix. Country codes

Code	Country
BE	Belgium
BR	Brazil
CA	Canada
CH	Switzerland
CN	China
DE	Germany
ES	Spain
FR	France
GB	Great Britain
HU	Hungary
IE	Ireland
IL	Israel
IN	India
IT	Italy
JP	Japan
KR	Korea
MY	Malaysia
NL	Netherlands
NO	Norway
RU	Russia
SE	Sweden
SG	Singapore
TH	Thailand
TR	Turkey
TW	Taiwan
US	United States