

Developing nanotechnology in Latin America

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Abstract This article investigates the development of nanotechnology in Latin America with a particular focus on Argentina, Brazil, Chile, and Uruguay. Based on data for nanotechnology research publications and patents and suggesting a framework for analyzing the development of R&D networks, we identify three potential strategies of nanotechnology research collaboration. Then, we seek to identify the balance of emphasis upon each of the three strategies by mapping the current research profile of those four countries. In general, we find that they are implementing policies and programs to develop nanotechnologies but differ in their collaboration strategies, institutional involvement, and level of development. On the other hand, we find that they coincide in having a modest industry participation in research and a low level of commercialization of nanotechnologies.

Keywords Nanotechnology development · Latin America · Research collaboration · Development · Strategies · International survey

Introduction

Through the manipulation of molecular-sized materials to create new products and processes with novel features due to their nanoscale properties, nanotechnology promises to be a leading driver of future technology-based business and economic growth around the world (Lux Research 2007). Advanced developed countries, including the US, Japan, and member states of the European Union, are investing billion of dollars annually in nanoscale research to build the scientific foundations for nanotechnology commercialization (Roco 2005; NSET 2007). China and Russia also are embarked upon major nanotechnology research programs (Applebaum et al. 2006; Kostoff et al. 2007; Zaitchik 2007). This presents both challenges and opportunities to other countries at medium levels of development. They have established science infrastructures and capabilities, but not of the scale and scope of the world's major R&D performing nations. Yet, through targeted investments and strategic collaborations, intermediate countries could leverage their R&D capabilities to absorb and advance new knowledge in

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nanotechnology research domains of relevance to their countries, be better placed to benefit from nanotechnology commercialization opportunities, and strengthen abilities to assess and manage potential nanotechnology risks.

This article investigates the development of nanotechnology in Latin America with a particular focus on Argentina, Brazil, Chile, and Uruguay. These countries form a contiguous block in the southern cone of Latin America and share various cultural and economic characteristics. All are middle-income countries (by the World Bank definition) with active research systems that receive from low-to-moderate levels of R&D investment. There are also important differences: Argentina (2004 population: 38.4 million) and particularly Brazil (183.9 million people) are bigger and more industrialized countries, whereas Chile (16.1 million people) and Uruguay (3.4 million people) are smaller and depend more on their natural resources. However, they are similar in terms of per capita income and population-adjusted R&D inputs and outputs (Table 1).

To date, international studies of the development of nanotechnology and its potential impacts have focused mostly on the leading countries for nanotechnology R&D and in so doing have highlighted the weaknesses of research on this topic for Latin America (Roco 2005; Besley et al. 2008). In this article, we undertake a fine-grain examination of the nanotechnology research and innovation landscape in selected Latin America countries. First, we review existing policies and programs to develop nanotechnology in Latin America and analyze institutions and areas of relative strength. We then put forward a framework for analyzing the development of R&D networks. In particular, we identify three potential strategies of nanotechnology research collaboration: within-country collaborations, including those in sub-national regional clusters; research collaborations among Latin American countries; and collaborations with nanotechnology researchers in leading countries outside Latin America. These strategies are not mutually exclusive, but each varies by scales of geographical and organizational proximity and in their likely research and innovation implications. With these strategic options in mind, we then analyze publication and patent data for Argentina, Brazil, Chile, and Uruguay to assess how nanotechnology R&D is developing in these countries and to examine

the relative importance of the three strategies of collaboration. Finally, we discuss policy implications for these and other Latin American countries and offer some broader conclusions.

The empirical analyses presented in this article draw on global databases of nanotechnology publications and patents developed at the Georgia Institute of Technology, using the definition of nanotechnology and methods described in Porter et al. (2008). A two-stage modularized Boolean approach to defining nanotechnology combined with expert panel review was used to operationalize a definition of nanotechnology and develop publication and patent datasets for the 1990–2006 (mid-year) time period. This approach identified more than 400,000 records in the Web of Science's Science Citation Index (WOS-SCI)¹ and nearly 54,000 abstracts of patents awarded in this same timeframe which were obtained from the MicroPatents database.² A new dataset was created for the country group comprising Argentina, Brazil,

¹ It is recognized that SCI varies in strength by subject area (SCI is excellent for most life and physical sciences, but not quite as strong in chemical, medical, and engineering research.) Also, SCI does not cover all scientific journals, and in its coverage is weaker for scientific journals that publish in languages other than English. However, although SCI does index publication records in other languages, our data for the period 1990–2006 show that Argentina, Brazil, Chile, and Uruguay usually publish in English for nanotechnology research (more than 98% of the publications). In terms of local languages, Brazil published more than 1% of its SCI nanotechnology articles in Portuguese, Argentina more than 1% in Spanish, and Chile more than 3% in Spanish. All SCI nanotechnology research articles from Uruguay are written in English. On the other hand, there is evidence that developing countries are not well represented in international databases when it comes to analyzing total scientific output, because they often publish in national journals (Gaillard 1992). However, it is not clear how significant this is for the emerging field of nanotechnology. A search of SciELO (Scientific Electronic Library Online,) which specializes in providing online access to scientific journals in Latin America and the Caribbean, indicates that most of the domestic journals in Argentina, Brazil, and Chile that publish nanotechnology-relevant articles, including national and university journals in physics, chemistry, and materials science, are indexed in SCI (whether they publish in English or not) and many articles in these journals are published in English (Uruguay is not a member of SciELO). In short, while SCI is certainly not complete, it appears that it does capture much of the region's output of scientific articles in nanotechnology.

² The patents database covers the USPTO, EPO, JPO, World Intellectual Property Office (WIPO), and patent offices of Germany, Great Britain, and France.

Table 1 Economic, population, science and technology, and government nanotechnology R&D for Argentina, Brazil, Chile, and Uruguay and selected reference countries (countries ranked by per capita income)

Country	GNI per capita US\$ PPP 2006 (thousands) ^{a,b}	Income group ^c	Population 2006 (millions) ^a	R&D spending (% GDP) ^{d,e}	Researchers in R&D ^{e,f} (per million population)	S&E articles 2005 ^g	Patents 2005 ^{e,h}	Government nanotechnology R&D (Estimated) US\$ 2006 ⁱ
USA	44.1	HIC	299.4	2.68	4,605	692.7	244	1,775
Japan	32.8	HIC	127.8	3.15	5,287	434.0	857	975
Germany	32.7	HIC	82.4	2.49	3,261	535.1	158	505
Spain	28.2	HIC	44.1	1.11	2,195	422.5	53	50 ^j
Russia	12.7	UMC	142.5	1.17	3,319	100.7	135	106
Mexico	12.0	UMC	104.2	0.40	268	37.8	1	12 ^k
Argentina	11.7	UMC	39.1	0.41	720	79.0	4	2 ^l
Chile	11.3	UMC	16.4	0.61	444	95.6	1	10 ^m
Uruguay	9.9	UMC	3.3	0.26	366	58.3	1	– ⁿ
Brazil	8.7	UMC	189.3	0.98	344	53.1	1	27–40 ^o
China	4.7	LMC	1,311.8	1.44	708	31.9	16	220
India	2.5	LMC	1,109.8	0.85	119	13.3	1	106

^a World Bank, World Development Indicators

^b Gross National Income per capita at Purchasing Power Parity (PPP). PPP exchange rates equalize purchasing power taking into account differences in costs between countries

^c World Bank classification of countries by GNI per capita (2007): HIC, high income; UMC, upper middle income; LMC, lower middle income

^d Research and development spending as a percent of Gross Domestic Product

^e United Nations Development Programme, Human Development Report, 2007/2008

^f Latest data to 2005

^g Science and engineering articles, from National Science Foundation, Science and Engineering Indicators, 2008, Appendix Table 5–34, denominator is 2005 population

^h Patents granted to residents

ⁱ 2006 Government funding on nanotechnology research (Lux Research 2007), except as noted. Conversions from € to US\$ at European Central Bank exchange rate for relevant year

^j 2006 estimate from data in Correia et al. (2007)

^k 2004 data in European Commission (2005)

^l Annualized 2005–2010 budget commitment of Fundación Argentina del Nanotecnología. Amount of additional public funds from other sources is unknown

^m 2005 estimate (Foladori and Fuentes 2007)

ⁿ In Uruguay, nanotechnology R&D funding is provided at the university for a few projects, total is unavailable

^o Estimated from data in Niosi and Reid (2007) and Malsch (2008b)

Chile, and Uruguay.³ This yielded a total of 7,309 publications and only 52 patents for the period 1990–2006. Since the total count of patents is very low, the analysis focuses mainly on publications with some additional comments about patenting activity.

³ This dataset comprises all records where at least one author affiliation is located in one of the four target countries.

What is going on in nanotechnology in Latin America?

Research publication performance

Several Latin American countries have set the development of nanotechnology as an objective to increase their competitiveness (Foladori 2006). However, scientific research has been concentrated primarily in

Table 2 Nanotechnology publications for Latin America and selected reference countries, 1990–2006^a

Country	Total nanotechnology publications 1990–2006 ^a	World Share (with Latin American share)	Nanotechnology publications per million people 2005
Brazil	5,456	1.2% (50.2%)	4.7
Mexico	2,487	0.6% (22.9%)	3.9
Argentina	1,318	0.3% (12.1%)	4.6
Chile	481	0.1% (4.4%)	4.5
Cuba	343	0.1% (3.2%)	4.4
Venezuela	335	0.1% (3.1%)	1.8
Colombia	301	0.1% (2.8%)	1.0
Uruguay	54	0.0% (0.5%)	2.6
Peru	45	0.0% (0.4%)	0.3
Costa Rica	30	0.0% (0.3%)	0.9
Bolivia	12	0.0% (0.1%)	0.1
Guadeloupe	9	0.0% (0.1%)	2.5
Panama	6	0.0% (1.1%)	0.3
Latin America	10,887	2.4% (100.0%)	3.1
China	51,620	11.5%	7.5
Germany	41,793	9.3%	59.6
India	9,399	2.1%	1.6
Japan	47,894	10.6%	48.5
Spain	9,675	2.1%	35.3
USA	101,205	22.5%	47.6

^a To first half of 2006

Source: Analysis of Georgia Tech global nanotechnology publication dataset. See Porter et al. (2008). World total for this time period = 450,465

three countries, Brazil, Mexico, and Argentina, which contributed about 85% of all nanotechnology publications from this continent during the period 1990–2006 (Table 2).⁴ In these countries, nanotechnology research activity in the field started in the early 1990s, but publication output did not begin to noticeably increase until the middle of that decade (Fig. 1)

At the aggregate level, Latin America's share of global nanotechnology publications grew in successive years between 1994 and 2002, rising to 3.6% of the world's nanotechnology publication output in the latter year. Since 2002, although the actual number of publications has continued to increase, the continent's relative share of world output has declined. In 2005, Latin America contributed 3% of the world's nanotechnology publications (Latin America's share

of world population was 8.6% in that year).⁵ In general terms, this relative decline reflects greater increases in research activity and publication in other leading countries. For example, between 2002 and 2005, annual nanotechnology publication rates increased by 57% for the US and 170% in China compared with 33% for Latin America. By country, Brazil and Mexico have continued to expand absolute numbers of publications, while in Argentina, Chile, and Uruguay there has been a relative standstill in publication growth in recent years (Fig. 1).⁶ In terms

⁴ At the aggregate level, Latin America contributed 2.6% of the world's total nanotechnology publications in that period. However, looking at its contribution per year, Latin America decreased from 3.6% of the total in 2002 to 2.5% in 2006. Generally speaking, this is the result of a relative increasing in research activity and publication in developed leading countries.

⁵ 2005 population data from Population Division of the Department of Economic and Social Affairs of the United Nations Secretariat, World Population Prospects, 2007 Revision, available at <http://esa.un.org/unup>. The UN definition of Latin America includes Mexico and the Caribbean.

⁶ Between 1994 and 2004, nanotechnology articles as a proportion of all published articles increased from 0.01 to 0.03—which is about the same proportion as the US. However, Brazil's 2004 specialization in nanotechnology publications is noticeably lower than other fast emerging Asian economies such as China (0.10), South Korea (0.09), and Taiwan (0.07) which have more strongly emphasized nanotechnology as part of their national R&D strategies (Data from Kostoff et al. 2006, Table 6).

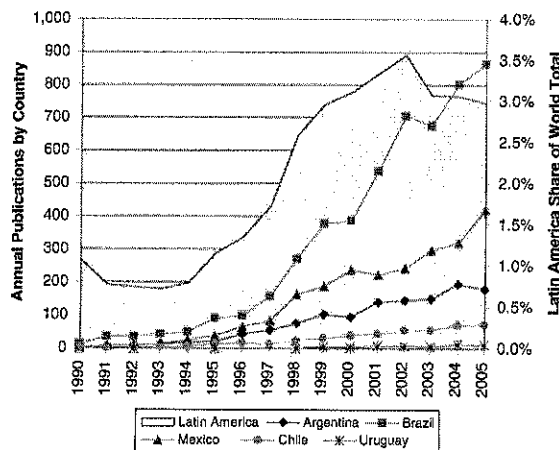


Fig. 1 Nanotechnology publications, annual, by leading Latin American countries and Latin American share of world total, 1990–2005. *Source:* Analysis of Georgia Tech global nanotechnology publications dataset

of research quality and impact, to the extent that this can be measured by citations recorded by SCI, the picture is also mixed. Nanotechnology articles authored in Argentina, Brazil, Chile, and Uruguay are less cited than the average for US authored articles, which is not unexpected (detailed in Table 4). While the impact trend is up slightly for Argentina and Chile when relative citations (as of mid-2006) for articles published in 2000 and 2004 are compared, it is down slightly for Brazil. Perhaps more significantly, while the relative impact trend is little changed in these Latin American countries, it has grown in other emerging economies, particularly in China and “Asian Tigers” (Singapore, Taiwan, and Korea.) For example, nanotechnology articles published in 2000 were relatively less well cited if authored in China than if authored in Brazil and similarly cited if authored in Argentina (as of mid-2006 compared with US articles published in the same year). However, for more recent articles published in 2004, Chinese-authored articles (although still less cited than US articles as of mid-2006) were attracting significantly more citations than Brazilian and Argentinean ones.⁷

⁷ Authors’ analysis of Georgia Tech global nanotechnology publications dataset. For Chinese nanotechnology articles published in 2000 and 2004, SCI citations relative to US articles by mid-2006 were 0.38 and 0.47, respectively. For Asian Tiger countries, the comparable averages were 0.44 and 0.51. See Table 3 in this article for Latin American comparisons.

R&D policies and programs

While research activity in nanotechnology began to pick up in Latin America in the 1990s, the implementation of dedicated nanotechnology-related policies and programs is a more recent phenomenon. For instance, nanotechnology policy in Brazil effectively started in 2001 with the creation of four institutional, multidisciplinary networks aimed at promoting research in the field. This initiative represented an important effort of the Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq)⁸ to develop nanotechnology in terms of human resources and funding. The Ministerio de Ciencia y Tecnología (MCT), the scientific community, and the private sector were the leaders in establishing the objectives of that initiative, including aims to balance regional development, integrate public and private research activities, and improve the technological level of Brazilian firms (Durán and De Azevedo 2002). According to Martins et al. (2007), during the period 2002–2005 those networks involved 300 researchers, 77 research and education institutions, and 13 companies, publishing more than a thousand research articles and obtaining more than 90 patents. Among the research areas that these networks sought to cover during this period were physics, chemistry, mathematics, medicine, biology, engineering, materials sciences, and computer sciences. The recent Rede BrasilNano program created ten new research networks to continue with that previous research,⁹ adding in this case a linking component between the program to develop nanotechnology and broader industry, technology, and trade policies (Invernizzi 2007). Furthermore, Brazil’s new National Program of Nanotechnology seeks to reach 1% of the global markets for materials, products, and processes based on nanotechnology (Goncalves da Silva 2003).

Mexico is second in Latin America by published nanotechnology articles (and also by population). In 2004, there were eleven nanotechnology research

⁸ CNPq is a government agency whose mission is to promote and stimulate the scientific and technological development of the country and contribute to the formulation of national S&T policy.

⁹ These new networks are still in an initial stage of implementation.

groups at three universities and two research institutes, working primarily in new materials development (Malsch 2004); in 2007, an external European mission identified more than a dozen institutions with active nanotechnology research programs, again with a strong presence in nanomaterials (NanoforumEULA 2007). A few companies are also commercializing nanotechnology in Mexico, although academic–industry relationships are reported as weak (Malsch 2004). An important aspect for Mexico is the link maintained with the US in terms of cooperation for high-technology development which, jointly with the geographic proximity to that country, are hoped to offer Mexico an advantage for future commercialization of nanotechnology compared with other countries of Latin America. There are already some initiatives for supplying the semiconductor and other high-tech industries. For example, the project for the Silicon Border Development Science Park started in 2006 with the goal of becoming the first high-tech park in Latin America that is specialized at the nanoscale (Foladori and Zayago 2007). However, Mexico does not have a national program for developing these technologies. Indeed, until 2005 there was no federal program financing, organizing, or regulating nanotechnology (Foladori 2006). Additionally, Mexico consistently faces challenges of retaining its most highly talented researchers in the face of superior research conditions and salaries in the US. Some authors have also pointed out the lack of adequate intellectual property protection in Mexico as an obstacle for developing nanotechnology in the country (Kraul 2003; Malsch 2004).

Argentina, the third-ranked nanotechnology publisher in Latin America, has also implemented nanotechnology policy measures, including the creation of Fundación Argentina de Nanotecnología (FAN).¹⁰ FAN is a non-profit, private institution created by the Argentinean government in 2005 to lead the development of nanotechnology in the country. Its objectives include the development of human resources and infrastructure, the promotion of collaboration between national public and private institutions, the promotion of international collaborations, and the establishment of priority research areas (Andrini and Figueroa 2007). The advisory

council of FAN has membership from Argentina's most important organizations in nanotechnology including a national university, a state-owned company, and four key government S&T and R&D institutions.¹¹ On the other hand, nanotechnology has been included as a strategic priority in the national S&T agency's medium term plan and the national congress has put forward a 10-year nanotechnology plan (Sametband 2005). Several networks for nanoscience research have been established, including four networks sponsored by the National Agency for the Promotion of Science and Technology (ANPCYT) for molecular, supramolecular and interface nanoscience; nanostructure materials; bionanostructures; and the design and simulation of nano devices and prototypes (Malsch 2008a). An Interdisciplinary Centre for Nanoscience and Nanotechnology involving about 100 scientists from multiple locations with support from five companies has been formed (Malsch 2008a), and other private companies have demonstrated interest in developing and acquiring nanotechnology in the areas of chemistry, materials, biology, and textiles. However, this has not been accompanied by major increase in private research funding. In sum, according to Fernández and Schatzmann (2007), the nanotechnology community in Argentina comprises about 200 researchers in several government and university labs and institutions and about 20 private companies.

These three Latin American leaders are followed by Chile in terms of nanotechnology publications. Between 1999 and 2006, two broader programs to improve the Chilean S&T system¹² funded selected nanotechnology initiatives at six different universities¹³ in the areas of physics, biology, and materials science. Despite this increased institutional

¹¹ The institutions in the advisory council are: Universidad de Buenos Aires (UBA), Instituto Nacional de Tecnología Agropecuaria (INTA), Comisión Nacional de Actividades Espaciales (CONAE), INVAP SE, Consejo Nacional de Investigaciones Científicas y Técnicas (CONICET), and Instituto Nacional de Tecnología Industrial (INTI).

¹² Chile recently implemented two main programs for improving R&D: the Millennium Scientific Initiatives (a top-down policy recommended by the World Bank) and, more recently, the Bicentennial Program of Science and Technology.

¹³ They are: Universidad de Chile, Universidad de Santiago de Chile, Universidad Técnica Federico Santa María, Universidad Andrés Bello, Pontificia Universidad Católica de Chile, and Universidad de Concepción.

¹⁰ Argentinean Nanotechnology Foundation.

involvement, Foladori and Fuentes (2007) point out that comparatively few researchers are working in nanotechnology in the areas of physics, chemistry, biology, and materials science.¹⁴ It is worth noting that recently Universidad de Santiago (one of the top Chilean universities working in nanotechnology) has announced joint research projects with universities in USA and Canada (Univiersia 2007).

The fifth-ranked Latin America country by absolute nanotechnology research output is Cuba (in relative terms, Cuba ranks second in Latin America by nanotechnology publications per million inhabitants). According to Cuba's Science and Technology Council (CCyT 2002), at least four institutions in this country have multiple years of research experience related to nanotechnology.¹⁵ Notwithstanding limited physical infrastructure, Cuba has produced a relatively large and well-trained group of scientists which are active in the development of nanotechnology, particularly nano-biotechnology (Foladori 2006). Available information on policy aims is limited to documents presented by the Cuban Academy of Sciences and the Ministry of Science, Technology, and Environment (CITMA) which point out the need for creating national capabilities in nanotechnology and establishing goals to work in related areas like mathematics, physics, chemistry, IT, and new materials (CCyT 2002).

Venezuela has published slightly less than Cuba. According to de la Vega et al. (2007), nanotechnology research in that country is clustered primarily in four institutions contributing 90% of the country's publications.¹⁶ These institutions also concentrate R&D investment, scholarships, and sponsored projects. Those authors found some nanotechnology patenting activity in the country, corresponding generally to

foreign inventors. However, to date, Venezuela lacks official policies or programs related to nanotechnology. More recent government initiatives are seeking to study the status of nanotechnology development in the country (de la Vega et al. 2007).

Colombia follows Venezuela in terms of publications. It established "advanced materials and nanotechnology" as a science and technology (S&T) priority in 2004 (Foladori 2006). In 2005, a Nanotechnology Council was established in the country, under the Colombian section of the Institute of Electrical and Electronics Engineers (IEEE). This council was created to participate, jointly with universities, research centers, industry, and the government, in the development of nanotechnology in the country.

The rest of the Latin American countries contributed, individually, less than 1% of the continent's publications in the period 1990–2006 (Table 2). At the head of this group of following countries is Uruguay, which is undertaking nanotechnology research through the G-Nanotec-Uy (Uruguay Nanotechnology Group,) a group led by 15 researchers working at different labs in Universidad de la República (the main university in this country)¹⁷ and Instituto Clemente Estable. Their work is concentrated in areas of biology, physics, and materials science. According to an evaluation made by the same group, the further development of nanotechnology activities in Uruguay requires the definition of objectives and prioritization in the national S&T strategy (Chiancone et al. 2007).

At least five other countries in Latin America are undertaking research in nanotechnology, namely Peru, Costa Rica, Bolivia, Guadeloupe, and Panama. These countries present different levels of initial development and interest in nanotechnology. For instance, in 2004, Costa Rica opened the National Laboratory for Nanotechnology, Microsensors and Advanced Materials (Lanotec.) which is the first center of this type in Central America.¹⁸ Other countries with very low activity in nanotechnology research, like Peru or Ecuador, have been working to

¹⁴ Foladori and Fuentes (2007) suggest that no more than 20 Chilean researchers are working in these disciplinary fields, excluding additional researchers that may be working in nanobiology.

¹⁵ They are: Universidad de la Habana (UH), Centro Nacional de Investigaciones Científicas (CENIC), Instituto Superior Politécnico José Antonio Echeverría (ISPJAE), and Universidad Central de las Villas (UCLV).

¹⁶ They are: Universidad Central de Venezuela (UCV), Universidad Simón Bolívar (USB), Universidad de los Andes (ULA), Instituto Venezolano de Investigaciones Científicas (IVIC), and Instituto Tecnológico Venezolano del Petróleo (INTEVEP).

¹⁷ This university concentrates roughly 70% of the country's human resources in research and about one-third of its total research expenditure.

¹⁸ This is part of the National Center for High Technology (CeNAT). The initiative was funded by the Costa Rica—United States of America Foundation for Cooperation, the Costa Rican Ministry of Science and Technology's incentive fund, and the Pro-Cenat Foundation (Vargas 2004).

include nanotechnology among their national S&T priorities.¹⁹

There is at least one joint initiative between the Latin American countries. The Centro Argentino Brasileño de Nanociencia y Nanotecnología (CABNN) is a virtual nanotechnology center bringing together research from groups working in Brazil and Argentina. It was created using the model of a previous cooperation experience in biotechnology, and its aim is using the science infrastructure of each country to develop joint projects, raise human resources capacity, create interchange grants for researchers, organize activities like forums and conferences, and increase interactions with industry (Almeida 2005; Diario LaU 2005). There are also multiple initiatives involving Latin American nanotechnology researchers with international projects sponsored by bilateral collaboration programs (particularly with the US, Germany, France, and the UK) and in some cases with European Commission support (Malsch 2008a, b). Generally, international support is a small although important complement to the collaborations that many Latin American research groups have established with colleagues in Europe, the US and elsewhere. These collaborations frequently draw on links established by Latin American researchers during graduate or post-graduate education and training abroad.

Although national agencies across Latin America indicate increased interest in promoting nanotechnology, public investment in nanotechnology R&D remains relatively modest (Table 1). Brazil—which leads in total government nanotechnology R&D spending in Latin America—has a high-end estimated 2006 investment of about \$0.21 per capita (equivalent to \$0.39 when adjusted for Purchasing Power Parity or PPP).²⁰ However, this is about three orders of

magnitude lower than the 2006 level of government nanotechnology R&D investment found in the US (\$5.84 PPP per capita) although it is comparable to the estimated levels for China (\$0.39 PPP per capita) and greater than for India (\$0.29 PPP per capita.) Chile is relatively higher up on the scale of public nanotechnology R&D spending per capita, at \$1.01 PPP per capita, while Argentina is lower at \$0.12 PPP per capita. These comparisons of government nanotechnology R&D need to be put in the broader context of the generally low levels of R&D spending as a proportion of the Gross Domestic Product found in Latin American countries (Table 1). Yet, despite limited overall levels of public nanotechnology R&D funding, external expert missions do note the presence of capable laboratories and research groups in nanotechnology in Latin America, even though problems related to limited financial resources and links with industry are also observed (see, for example, mission reports on Argentina and Brazil in Malsch 2008a, b).

Societal dimensions of nanotechnology

Any assessment of strategies for developing nanotechnology in Latin American countries needs to take into account broader considerations and debates about the potential impacts (both positive and negative) of nanotechnology. Although nanotechnology is anticipated to lead to advances in many technological fields, multiple risks and societal concerns have also been identified, including health and environmental risks and needs for improved regulation (Glanzel et al. 2003; Roco 2003; Maynard 2006; Besley et al. 2008). This has given rise to uncertainty about not only the scale but also the distribution of nanotechnology's potential social, economic, health, and environmental impacts and risks (Cobb and Macoubrie 2004).

Reflecting these concerns and driven by desires to bolster the governance of nanotechnology development, initiatives have been sponsored in several advanced countries to analyze the broad range of impacts associated with nanotechnology and, in some cases, to engage stakeholders and the public, in dialogue and deliberation. How such efforts will constructively change the development of nanotechnology and its impacts remains to be seen (Bennett and Sarewitz 2006), but they are underway. For example, in the US, the consideration of “ethical,

¹⁹ For instance, the national S&T agency of Ecuador (Secretaría Nacional de Ciencia y Tecnología—SENACYT) has included nanotechnology as a priority in its most recent policy document (Política Nacional de Ciencia, Tecnología e Innovación 2005–2010.) Also Peru established similar priorities in an S&T plan for competitiveness and human development for 2006–2021 (Plan Nacional Estratégico de Ciencia, Tecnología e Innovación para la Competitividad y el Desarrollo Humano—PNCTI).

²⁰ Sources for government spending on nanotechnology R&D as indicated in Table 1. For Latin American countries, estimates are based on available information and may be under-reported. Purchasing Power Parity (PPP) ratios were calculated based on World Bank, World Development Indicators, 2006, which is also the source of population estimates.

legal, environmental, and other appropriate societal concerns” in the development of nanotechnology is required by legislation,²¹ nanotechnology research centers are obliged to consider these issues, and new centers and projects have been sponsored to address these concerns (NSET 2004, 2005; Sarewitz and Guston 2004). Initiatives to consider the societal aspects of nanotechnology have also been launched in Europe and Japan (RAE 2004; Fogelberg and Sanden 2008; Ishizu et al. 2008).

In Latin America, the level of resources available for societal assessment is far lower than in developed countries. Yet, there is recognition that intermediate and developing countries could be vulnerable to risks associated with the application of nanotechnology, particularly given weaknesses in regulatory systems, yet may also lag behind developed economies in gaining economic benefits from this emerging technology (Invernizzi 2007; Invernizzi and Foladori 2005). For example, Invernizzi (2007) observes that nanotechnology in Brazil has been embraced and promoted by scientific elites as a mean for progress, efficiency, and competitiveness, but increasing social and economic inequalities in the country may actually prevent the technological benefits to be equally distributed. Indeed, in more general terms, Invernizzi and Foladori (2005) point out that the dominant socioeconomic structures in Latin American countries may hinder the deployment of nanotechnology applications that could provide benefits for the poorest groups. For example, these authors suggest that while quantum dot technologies have the potential to detect HIV/AIDS molecules at early onset, overstretched medical systems and an inability to afford expensive new treatments may limit use in developing countries. Moreover, they fear that even if nanotechnology in areas such as water filtration is applied in developing countries (including Latin America,) the poor majorities in these countries will not immediately benefit.

Collaboration strategies for nanotechnology development in Latin American countries

In seeking to develop nanotechnology in Latin America, both in terms of building research activities

and in influencing pathways for innovation and utilization, the level and character of research collaboration is an important factor. Since research resources are limited in all Latin American countries, collaboration can be helpful in leveraging available expertise and facilities, including providing access to equipment and instruments for researchers that lack such equipment in their home labs. Even more significantly, given the convergent nature of nanotechnology, research collaboration can be fundamental to undertaking interdisciplinary research, accessing up new sources of knowledge, and identifying and acting upon significant research problems (Heinze and Bauer 2007; Heinze et al. 2008). Research collaborations may also speed the transfer of knowledge for the deployment of nanotechnology, for example through collaboration between leading researchers in global centers and researchers in developing countries or, within a country, by teaming between academic and corporate researchers.

Although the possible permutations of research collaboration are many, we suggest that for Latin American countries there are three principal strategies for collaboration for developing nanotechnology: (1) within-country collaborations focusing on national priorities and targets; (2) supra-national regional collaborations with other countries in Latin America; and (3) international collaborations with researchers in countries outside Latin America, particularly in leading centers in advanced countries.

As previously noted, these strategies are not mutually exclusive, but each has different emphases with regard to geographical and organizational proximity and may have diverse implications in terms of research and application implications. For instance, a strategy to foster within-country collaborations will be based on indigenous capabilities and may reflect specific national goals for industry or sector targeting and meeting basic local demands or needs. There may also be longer-term goals of developing internal capabilities to develop products that can reach global markets through key export sectors. Emphasizing this strategy would require the involvement of key national groups²² with, probably, government

²¹ Twenty-first Century Nanotechnology Research and Development Act, 2003, PL 108–153, 2(b)(10).

²² Namely: main S&T actors, universities, industry, financial community, and NGOs.

coordination to establish national priorities and coordinate the national effort.²³

The second strategy is one where research collaborations are developed across countries in Latin America. There are already existing regional alliances between major countries. For example, Argentina, Brazil, and Uruguay are permanent members of the regional trade agreement MERCOSUR,²⁴ whereas Chile has an associate member status with this block. Conceivably, new research collaborations in nanotechnology may build upon such frameworks, as well as historical links, patterns of faculty and student exchange, and shared language (particularly for the Spanish-speaking countries). At present (and for the foreseeable future) such “Southern collaboration” linkages do not have anywhere near the funding levels or research infrastructures that, for example, are made available to supra-national collaboration through the European Union’s Framework Programmes or Joint Research Centres. But inter-regional collaborations in Latin America could allow nanotechnology research to be undertaken with a more diverse set of actors.

The third strategy involves the development international research collaborations and alliances outside Latin America, particularly with leading international centers in the US, Europe, and other developed countries. Such linkages allow Latin American researchers opportunities both to tap into the frontiers of research and development and to catch-up with or replicate research done by technology leaders. At the same time, global collaborations may lead to technological developments that are more 3 with foreign rather than local interests, although in some cases developed countries maintain research programs which encourage their researchers to work with colleagues in developing countries on topics of particular relevance to the latter. Efforts toward international alliances are likely to be led by universities and research institutes (with perhaps the support

of government departments, but not their management).

In this article, we use data on nanotechnology publication for Argentina, Brazil, Chile, and Uruguay to tease out clues as to the relative emphasis placed on each collaboration strategy by these Latin American countries. These countries not only represent a contiguous bloc in the southern cone of Latin America, but also offer contrasts in terms of nanotechnology R&D standing. Brazil is the largest economy on the continent and is the Latin American leader in nanotechnology R&D output. Argentina and Chile represent two medium-sized Latin American countries, with medium levels of nanotechnology R&D output. Both these countries have active nanotechnology R&D policies and programs. Uruguay represents an example of a small Latin American country, with a modest nanotechnology R&D effort.

For each of the four countries, we develop a series of variables, including ones related to co-authorship patterns, the organizational characteristics of first authors, institutional concentration, and research areas (see Table 3 for full variable list). We test for each of the three plausible collaboration strategies described above, hypothesizing that each strategy will be associated with different mixes of these variables. For example, a focus on national priorities is likely to be characterized by nanotechnology research led by single national institution or national collaborations and, if research is led by government labs, this would be also observed in first authorships. A focus on national priorities may also involve increasing research activity in industry (private or state-owned firms) and research areas aligned with key national industry sectors. On the other hand, if there is a focus on international alliances, we would expect to see this characterized by increasing co-authorship with international leading centers, institutional concentration, and prevailing academic first authorships. In this case, the research areas would likely be more aligned with leading centers’ research and less related to national demands. Finally, a focus on Latin American regional collaboration would be indicated by co-authorships at the inter-regional level, led by either academic or government researchers.

In the next section, we proceed by mapping the current profile of nanotechnology research for the four Latin American countries that we have selected

²³ For example, as implemented by the US federal government through its National Nanotechnology Initiative (NSET 2004) and in similar national initiatives in other advanced economies (Roco 2005).

²⁴ The “Southern Common Market” (MERCOSUR) was created by Argentina, Brazil, Paraguay, and Uruguay in March 1991. The agreements of these countries include goals like gradual elimination of tariff barriers and harmonization of the macroeconomic policies.

Table 3 Hypothesized strength of relationships between variables and main strategic components for elaborating nanotechnology development strategies in Latin America

Variables in dataset	Strategic components (Anticipated level)		
	National focus	International alliances	Regional collaborations
Co-authorship intl. (all)	Low	Moderate	Low
Co-authorship intl. leading centers	Low	High	Low
Co-authorship regional neighbors	Moderate	Low	High
Single, natl. Institution	High	Moderate	Low
Natl. Collaborations	High	Moderate	Low
Institutional concentration	Low	High	Low
Acad. first author	Moderate	High	Moderate
Gov. first author	High	Low	Moderate
Research areas/natl. needs alignment	High	Low	Moderate

Notes: In each cell is represented the extent to which the variable is positively related with each strategy, ranging from less related (Low) to more related (High)

for detailed analysis to identify the balance of emphasis upon each of the three strategies. Following this, in the concluding section, we review the strategic research collaboration options and consider implications for nanotechnology R&D policy.

Country analysis: nanotechnology development in Argentina, Brazil, Chile, and Uruguay

We analyze nanotechnology developments using data extracted from the Georgia Tech global nanotechnology publication and patent databases, as discussed in the introductory section. The data provide insights about how nanotechnology research is organized within the four selected countries (Argentina, Brazil, Chile, and Uruguay), how much research collaboration exists, and what are the components emphasized in the strategies of these countries.

Brazil is clearly the leader in nanotechnology research activity in this group, followed by Argentina, Chile, and Uruguay, in that order (Table 4).²⁵ In Brazil, about 255 different institutions are undertaking nanotechnology research, with universities as the most active publishers. Government labs and industry publishing levels are surprisingly low in Brazil, Chile, and Uruguay, whereas in Argentina four

government labs are among the top 10 institutions with more than 40% of the national research (Table 5). It is worth noting that in Uruguay almost all research activity is concentrated in one university (Universidad La República.) Domestically undertaken research prevails in Brazil (comprising about two-thirds of all published nanotechnology research) rather than collaboration with international leading centers²⁶ or regional co-authorships. This is in contrast to the case of Uruguay, where there are more international and, to less extent, regional collaborations (80% of the research is done with regional and international partners). Argentina and Chile present more average values: half of the nanotechnology publications of Argentina and 58% of Chile's are co-authored with researchers from other countries (Tables 4, 6). This general pattern is not unexpected, in that the smaller a country's R&D system, the more likely that its researchers will seek external collaborations. However, there are variations. For example, in its external collaborations, Chile is much more likely than Argentina to collaborate with other regional MERCOSUR neighbors.

As suggested by the dominant types of research institutions, authors from universities lead nanotechnology research in Brazil, Chile, and Uruguay, with a relatively low participation of government scientists in first authorships (Table 4). In the case of Argentina, government researchers have relatively more

²⁵ Over the period 1990–2006, Brazil ranked 19th among all 101 countries globally with nanotechnology publications by cumulative total of nanotechnology publications. Comparative rankings for the other countries were: Argentina 34th, Chile 46th, and Uruguay 72nd. Source: Georgia Tech nanotechnology publication dataset (see Porter et al. 2008).

²⁶ International collaborations with leading centers include collaborations with USA, France, Spain, Germany, Italy, England, Japan, Canada, Russia, and China.

Table 4 Nanotechnology research profiles, Brazil, Argentina, Chile, Uruguay

	Brazil	Argentina	Chile	Uruguay
Organizations (number)	Nanotechnology research publishing organizations			
Universities	144	31	20	1
Gov Labs	61	23	4	1
Industry	30	6	3	
Other	20	14	1	
Total	255	74	29	2
Articles (published 1990–2006) ^a	Publications			
Total	5,456	1,318	481	54
Per 100,000 people	2.97	3.27	2.95	1.56
Institutional concentration (Herfindahl)	0.07	0.09	0.12	0.83
Relative to US articles (same publication year)	SCI Citations 2006 ^a			
Published in 2000	0.37	0.40	0.26	N/A
Published in 2004	0.41	0.37	0.30	0.49
Organization (percent) ^b	First authorships			
Academic	74.8	54.1	69.2	48.1
Government	5.7	21.5	0.0	1.9
Industry (private)	0.2	0.1	0.0	0.0
Industry (public)	0.8	0.0	0.2	0.0
Hospital	0.1	0.4	0.0	0.0
Other (foundation, association)	0.1	0.5	0.0	0.0
Collaboration type (percent)	Co-authorships			
Co-authorship international (all)	36.1	49.5	58.4	79.6
Co-authorship international leading centers ^c	26.2	39.0	37.6	37.0
Co-authorship intra-MERCOSUR	2.7	7.9	17.0	48.1
Single, national institution	28.6	26.1	18.3	14.8
National collaboration (2+ local institutions only)	35.3	24.4	23.3	5.6
Article subject categories (percent) ^d	Primary subject areas			
Physics	44.5	39.6	32.6	35.2
Chemistry	22.3	31.1	31.6	24.1
Materials Science	32.0	25.9	24.9	29.6
Biology	4.9	6.2	10.0	7.4
Engineering	7.1	6.0	3.7	11.1
Medicine	5.7	4.1	9.8	5.6
Electronics	4.5	3.0	4.0	7.4
Geology, Environmental, Energy	1.4	2.8	3.5	11.1
Agriculture	0.8	1.7	1.0	0.0
Mathematics, Computer Science	0.6	0.5	0.2	0.0

Source: Analysis of Georgia Tech global nanotechnology publication dataset

^a To first half of 2006

^b Totals do not add up to 100% because some publications have first authors from other countries (international or regional collaborations)

^c International collaborations with leading centers include collaborations with USA, France, Spain, Germany, Italy, England, Japan, Canada, Russia, and China

^d Totals add up to more than 100% because some publications are categorized in more than one subject area

leading participation as first authors. In addition, industry first authorship level is very low in all four countries. Although it is expected that industry will always be a much lower producer of research publications than the academic and government sectors, the levels found in our selected Latin American countries are particularly low. Industry first authorship of papers is close to zero in Uruguay and only a small fraction of 1% in Argentina and Chile. While nanotechnology research in Brazil involves more private and state-owned firms, they only account for roughly 1% of first authorships. By comparison, the equivalent industry authorship rate is 11% in the US and 2% in China, the latter being more comparable to Latin America (Shapira and Wang 2008). For Latin America, as in other emerging economies, the relatively small role of industry in nanotechnology R&D publication suggests weaknesses not only in research but also in absorptive capabilities to be able to industrially apply new nanotechnology innovations whether developed at home or elsewhere.

In spatial terms, nanotechnology research in our four focal countries is concentrated in an arc of cities mostly along the Atlantic and Pacific coasts. The top five leading regional nanotechnology research producing complexes (by articles published) are Sao Paulo, Campinas, Sao Carlos, and Rio de Janeiro in Brazil and Buenos Aires in Argentina. A second tier of regional complexes comprises Porto Alegre, Belo Horizonte Araraquara, Brasilia, Curitiba, Maringa, and Recife (Brazil), Santiago (Chile), and La Plata and San Carlos De Bariloche (Argentina) (Fig. 2).

In all four countries, there is a specialization in nanotechnology research in terms of both institutional participation and subject areas. Nanotechnology is mostly concentrated in three areas: physics, chemistry, and materials science, with only Uruguay showing relatively more publications in engineering and in geology, environmental, and energy (both areas with more than 11% of the country's publications) (Table 4). Nanotechnology research in this group of countries is also concentrated in relatively few institutions. Among the top 20 research institutions in the region there are 14 in Brazil, five in Argentina, and one from Chile. In Brazil, the majority of leading publishers are federal universities which contributed more than 80% of the region's publications (Table 5). Furthermore, there are two Brazilian

universities (Universidade de São Paulo and Universidade Estadual de Campinas) which produce more than one-third of the nanotechnology research in our selected country group.

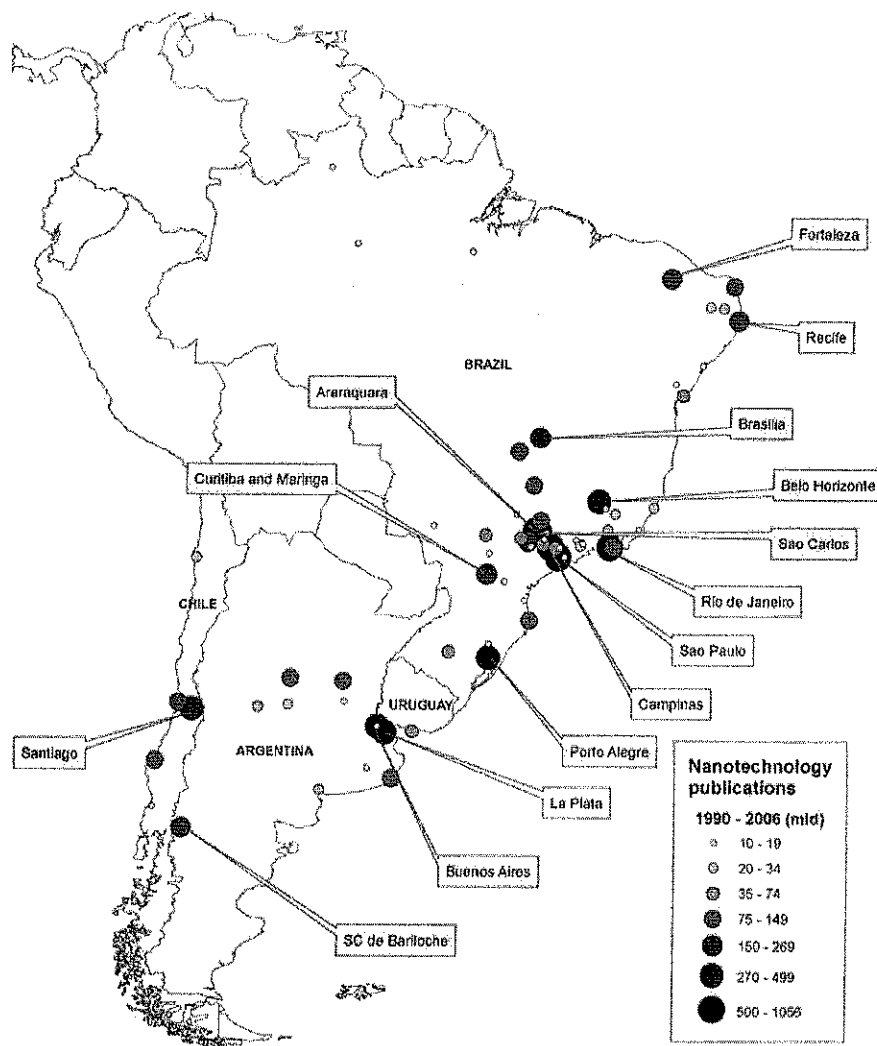
A network analysis further helps in understanding how research is done within these countries. We represented graphically the relationships between research institutions and obtained a measure of centrality for the top 50 institutions from Argentina, Brazil, Chile, and Uruguay (Fig. 3). As expected, most of the institutions in this network are from Brazil and few of them are from Argentina and Chile. Only one institution is from Uruguay. Generally speaking, the network shows the importance of collaborations within each country, particularly in Brazil. More interesting is that more publications do not make research institutions more central in this network, as shown by a measure of degree centrality. For example, Universidade Estadual de Campinas has about 40% less publications than Universidade de São Paulo (both from Brazil) and both have the same degree centrality (i.e., both are equally well connected to this regional network) (Table 7).

The analysis of patents would also help in understanding the development of nanotechnology commercialization efforts in these countries. However, the lack of patenting activity impedes detailed investigation. In our data, we find only 45 patent awards in the period 1990–2006 for Brazil, the most active country in our group.²⁷ Other studies have suggested that nanotechnology patents granted by the Brazilian patent office are a little higher, but not by much.²⁸ In general, patenting activity across all domains in Latin American countries is low compared to research publication output. For example, whereas there are about three science and engineering publications relative to every resident patent grant in the US and Germany and eight in Spain, the equivalent numbers for Argentina and Brazil are 20

²⁷ Other research confirms the very limited patenting in the nanotechnology domain in Brazil. See, for example, Antunes (2004) who (with a narrower search term than we used) finds only two Brazilian nanotechnology patents out of more than 12,000 nanotechnology patents registered with the European Patent Office between 1994 and 2004.

²⁸ According to Martins et al. (2007), the Ministerio de Ciencia y Tecnología of Brazil reported more than 90 patents as a result of the activities of the nanotechnology research networks between 2002 and 2005.

Fig. 2 Leading Nanotechnology Research City-Regions in Brazil, Argentina, Chile, and Uruguay. *Source:* Analysis of Georgia Tech global nanotechnology publication dataset. Only cities with 10 or more nanotechnology publications (1990–2006 mid) are shown



and 53, respectively (calculated from data in Table 1) Niosi and Reid (2007) note that public researchers and academics in Latin American often face constraints in undertaking private sector activities and incentives to encourage patenting are weak. This situation seems to be continuing for nanotechnology, foreshadowing issues in the industrial exploitation of nanotechnology research and knowledge in our four study countries as well as elsewhere in Latin America.

Policy implications

Our findings suggest policy issues and implications for our group of Latin American countries. For

example, all four countries present some level of institutional concentration in their research. This is most pronounced in the case of Brazil, which seems to follow a strategy based on national targets rather than international collaboration, as suggested by the implementation of programs aimed at creating national research networks, like the Rede BrasilNano program. The institutional concentration of research is even greater in Uruguay (which is a much smaller country), but in this case it is consistent with its emphasis in regional collaborations and less developed S&T system. Whether greater incentives for international collaboration in nanotechnology research in Latin America are appropriate is an issue that policymakers in these countries may wish to consider.

Table 5 Most active institutions undertaking nanotechnology research by country (with number of identified nanotechnology publications and share of total publications for the four countries, 1990–2006)^a

Brazil		Argentina		Chile		Uruguay	
Universidade de São Paulo	1,424 (19.5%)	Universidad Nacional de La Plata	291 (4.0%)	Universidad de Chile	123 (1.7%)	Universidad La República	53 (0.7%)
Universidade Estadual de Campinas	997 (13.6%)	Universidad de Buenos Aires	258 (3.5%)	Universidad de Concepción	93 (1.3%)	Instituto de Investigaciones Biológicas Clemente Estable---IIBCE	2 (0.0%)
Universidade Federal de São Carlos	592 (8.1%)	Comisión Nacional de Energía Atómica	216 (3.0%)	Pontificia Universidad Católica de Chile	88 (1.2%)		
Universidade Estadual Paulista 'Júlio de Mesquita Filho'	431 (5.9%)	Consejo Nacional de Investigaciones Científicas y Técnicas	158 (2.2%)	Universidad de Santiago de Chile	86 (1.2%)		
Universidade Federal do Rio de Janeiro	401 (5.5%)	Universidad Nacional de Córdoba	153 (2.1%)	Pontificia Universidad Católica de Valparaíso	62 (0.8%)		
Universidade Federal do Rio Grande do Sul	322 (4.4%)	Centro Atómico Bariloche	114 (1.6%)	Universidad Técnica Federico Santa María	54 (0.7%)		
Universidade Federal de Minas Gerais	294 (4.0%)	Universidad Nacional de Mar del Plata	88 (1.2%)	Universidad Católica del Norte	26 (0.4%)		
Universidade de Brasília	262 (3.6%)	Instituto Balseiro	68 (0.9%)	Universidad Austral Chile	20 (0.3%)		
Universidade Federal do Ceará	201 (2.8%)	Universidad Nacional del Sur	49 (0.7%)	Universidad Tecnológica Metropolitana---UTEM	16 (0.2%)		
Universidade Federal de Pernambuco	175 (2.4%)	Universidad Nacional del Litoral	48 (0.7%)	Comisión Chilena de Energía Nuclear---CCHEN	13 (0.2%)		

^a To first half of 2006

Source: Analysis of Georgia Tech global nanotechnology publication dataset

Moreover, we note the weakness of industry involvement in nanotechnology research. For countries like Chile or Uruguay this is perhaps not surprising, given the emerging state of development in their industrial sectors. The weakness of industry involvement is most significant for Brazil (where

conglomerates and internationally oriented companies have emerged in technology and natural resource sectors) and, to less extent, Argentina. Possible explanations for low industry involvement include the still early stage of nanotechnology development in Latin America, the weakness of domestic corporate

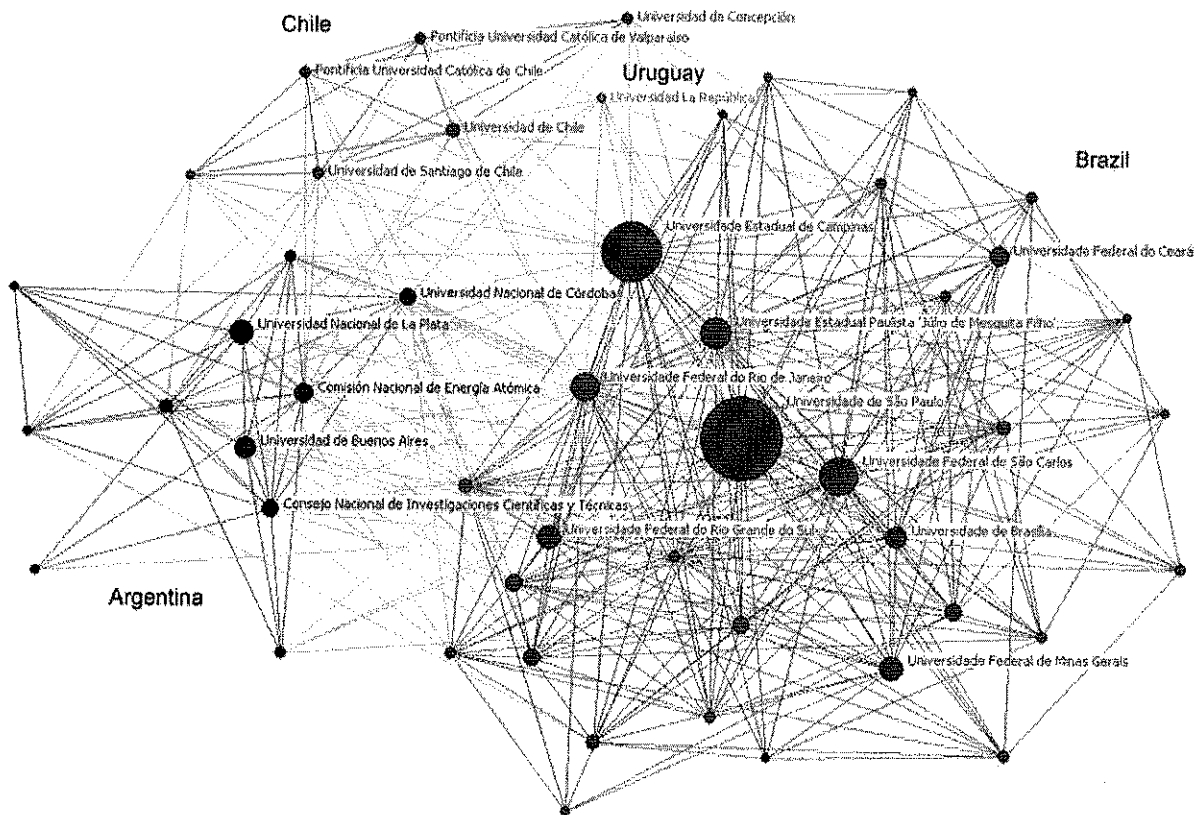


Fig. 3 Network of top nanotechnology institutions, selected countries. *Notes:* This network represents graphically the relationships between the top 50 research institutions in Argentina, Brazil, Chile, and Uruguay. Each node represents

one institution and its size represent the country and the number of publications for the entire 1990–2006 (mid) period, respectively. The lines represent co-authorships

R&D, the dominance of foreign multi-national branches who draw on their own company rather than local universities for R&D, a general lack of industry awareness of nanotechnology, and bureaucratic barriers faced by industry in working with universities. Whatever the causes, this finding foreshadows weaknesses not only in industry R&D but also in the absorptive capabilities of firms in Latin America to apply nanotechnology applications. In Brazil, given its efforts to develop aerospace, electronics, and other advanced technologies, as well as in the resource-intensive areas of all the countries (such as the prominent minerals, metals, and pulp and paper sectors in Chile) there may be unexploited opportunities for collaborative nanotechnology R&D with industry in nanomaterials and other nanotechnology domains.

Related to this, we observe the concentration of nanotechnology research in a few disciplines and

sectors in the four focal countries.²⁹ Although this finding is not surprising when compared with results of previous research, we suggest that these countries might consider strategies that seek to better align public R&D with industry and innovation priorities. At the same time, given the convergent scientific characteristics of nanotechnology, any approach should incorporate different disciplines (de la Vega

²⁹ Further research in this aspect should be made to draw more definitive conclusions. Previous research has shown that, for example, each one of the areas of physics, chemistry, and materials science, accounts for 50% or more of the total world publications in the period 1998–2001 (some publications are related to more than one area) (Glanzel et al. 2003). On the other hand, the proportion of publications in areas like Electrical & Electronic Engineering seems to be relatively low even at the worldwide level. For example, Hullmann and Meyer (2003) found that, by 1999 only 3% of worldwide nanotechnology publications were in the Electrical & Electronic Engineering area.

Table 6 Share of nanotechnology publications co-authored with other countries (percentages)

Country	Brazil	Argentina	Chile	Uruguay
Brazil	–	6.5	11.6	14.8
Argentina	1.6	–	3.1	9.3
Chile	1.0	1.1	–	24.1
Uruguay	0.1	0.4	2.7	–
USA	9.4	12.0	7.3	11.1
France	5.3	4.9	8.7	5.6
Spain	2.2	13.5	13.5	11.1
Germany	4.3	5.0	4.4	0.0
Italy	2.3	5.0	1.5	5.6
England	1.9	2.0	2.3	1.9
Japan	2.2	1.1	0.4	1.9
Canada	1.6	1.0	2.1	0.0
Cuba	1.5	0.1	0.8	0.0
Russia	1.4	0.3	0.0	0.0
Portugal	1.2	0.6	0.8	0.0
Belgium	1.0	0.2	1.2	1.9
Mexico	0.4	1.8	2.3	0.0
China	0.8	0.5	1.0	1.9

Source: Analysis of Georgia Tech global nanotechnology publication dataset, 1990–2006 (mid)

et al. 2007) as intended by, for example, by the Brazil multidisciplinary research programs. However, the data suggest that nanotechnology research may be not fully aligned with all key industry sectors. For example, there may be needs for additional efforts at nanotechnology interfaces in engineering and electronics in Brazil, and biology and agriculture in both Argentina and Uruguay. On the other hand, Chile is undertaking nanotechnology research in more diverse areas including biology, which is related to important sectors for the country such as forestry and fishing. We note that allying research with economic sectors and potential commercialization targets is not an insignificant task, and even in the leading international centers is not clear what (and how) opportunity area in nanotechnology should best be targeted (Zucker and Darby 2005). Still, there seem to be challenges here for Latin American countries in the mix of research areas: at present, research occurs where academic presence is strongest, but these areas may not always mesh with economic sector opportunities. At the same time, given the existing problems of research scale and

resources, it may not be feasible for most Latin American countries to develop new research areas.

We found that “Southern” (or intra-MERCOSUR) collaboration levels are relatively low in these four countries. In spite of wide economic differences, we wonder if more emphasis on inter-regional collaborations to implement strategies that take advantage of shared research targets may be helpful. For Uruguay this is clearly an important component of its strategy. Considering it has few research institutions and relatively low industrial development, this strategy is central to at least minimally exploit nanotechnology without having a strong national S&T system. For the other countries, intra-MERCOSUR collaboration also represents an opportunity. Brazil and Argentina are aware of this and have implemented a joint program, even though we were not able to find evidence of significant results from such collaborations.

Moreover, our data show relatively low government involvement in nanotechnology research publication, except for Argentina where there are several governmental labs that are actively involved in research. However, the role of government clearly may extend beyond this. Nanotechnology policies may give the role of broker to government agencies to enable knowledge transfer, sharing, and exchange between industry and academia. These agencies may also help in coordinating national R&D efforts and promote broader participation and citizen input on the use of nanotechnology applications (Chiancone et al. 2007; Invernizzi 2007). Furthermore, they can design regulation schemes to ensure the development of nanotechnology according to social and environmental standards (Maynard 2006).

Finally, the lack of nanotechnology patenting activity has two possible explanations. The first is that these countries are in an early stage of nanotechnology development and only after some years they will be able to transform research knowledge to intellectual property that can be used for the commercialization of nanotechnology applications and nanotechnology-based products. The second explanation has more policy implications: not only may these countries be undertaking nanotechnology research that is not aligned to local industry priorities but there may also be insufficient incentives for researchers to collaborate with incumbent industries and to initiate their own start-up enterprises. If Latin

Table 7 Freeman degree centrality based on nanotechnology publication co-authorships for the top 50 Latin American research institutions

Institution	Degree	NrmDegree
Universidade de São Paulo	39	79.592
Universidade Estadual de Campinas	39	79.592
Universidade Federal do Rio de Janeiro	35	71.429
Universidade Federal de São Carlos	33	67.347
Universidade Estadual Paulista 'Júlio de Mesquita Filho'	30	61.224
Universidade Federal do Rio Grande do Sul	27	55.102
Centro Brasileiro de Pesquisas Físicas	26	53.061
Comisión Nacional de Energía Atómica	22	44.898
Universidade de Brasília	21	42.857
Universidade Federal do Paraná	21	42.857
Associação Brasileira de Tecnologia Luz Síncroton	21	42.857
Universidad Nacional de Córdoba	20	40.816
Universidade Federal Fluminense	19	38.776
Universidade Federal de Pernambuco	18	36.735
Universidad Nacional de La Plata	18	36.735
Pontifícia Universidade Católica do Rio de Janeiro	18	36.735
Universidade Federal de Minas Gerais	16	32.653
Universidad de Buenos Aires	15	30.612
Consejo Nacional de Investigaciones Científicas y Técnicas	15	30.612
Centro Atómico Bariloche	15	30.612

Notes: The analysis was made based on a symmetric matrix where the cells contain the number of co-authorships for the top 50 institutions in Argentina, Brazil, Chile, and Uruguay. Only the top 20 institutions are shown in the table. The Freeman degree centrality is defined as a measure of the degree of inequality or variance in the network as a percentage of that of a perfect star network of the same size. In a star network, all the actors but one have degree of one, and the "star" has a degree of the number of actors minus one (Freeman 1979). The normalized degree (NrmDegree column) is a measure relative to the size of the network, with a maximum of 100

American S&T policymakers want to foster the development of nanotechnology and increase transfer to and take-up by key industry sectors, they may need to encourage research and incentives that can lead to the commercialization of new technologies in national and international markets. For this, it may be necessary to increase industry-academy collaborations, intellectual property protection, and enterprise support—all pending tasks for Latin American countries (Kraul 2003; Fernández and Schatzmann 2007; Foladori and Fuentes 2007).

Concluding comments

We have seen that Latin American countries, each one at its own scale, are implementing policies and programs to develop nanotechnology. However,

almost all scientific research is concentrated in few countries and patenting is infrequent. Among the group comprising Argentina, Brazil, Chile, and Uruguay (the focus of this article), Brazil is clearly the leader in nanotechnology research, followed by Argentina. Chile is increasingly involving more institutions in nanotechnology research and looking for regional and international collaborations, while Uruguay concentrates almost all nanotechnology research in one institution. The assessment of data about nanotechnology publications suggests that Brazil is pursuing a strategy based on national targets, whereas Uruguay's strategy is based more on regional collaborations. On the other hand, Argentina and Chile rely more on national and international collaborations, respectively. Nanotechnology research in these four countries is concentrated in core disciplines of physics,

chemistry, and materials science. This may not facilitate the development and use of nanotechnology in other key economic sectors for these countries (e.g. agriculture). The available patent data does not suggest any significant orientation to the commercialization of nanotechnology in these countries. In sum, the assessment of potential strategies that these and other Latin American countries may pursue suggests that they may wish to focus additional attention to various forms of research collaboration in nanotechnology, but they also need to reconcile this with challenges of ensuring relevance for national development, commercialization, and societal impact.

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