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Globalization and de-globalization in nanotechnology research: the role of China

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Abstract The share of nanotechnology publications involving authors from more than one country more than doubled in the 1990s, but then fell again until 2004, before recovering somewhat during the latter years of the decade. Meanwhile, the share of nanotechnology papers involving at least one Chinese author increased substantially over the last two decades. Papers involving Chinese authors are far less likely to be internationally co-authored than papers involving authors from other countries. Nonetheless, this appears to be changing as Chinese nanotechnology research becomes more advanced. An arithmetic decomposition confirms that China's growing share of such research accounts, in large part, for the observed stagnation of international collaboration. Thus two aspects of the globalization of science can work in opposing directions: diffusion to initially less scientifically advanced countries can depress international collaboration rates, while at the same time scientific advances in such countries can reverse this trend. We find that the growth of China's scientific community explains some, but not all of the dynamics of China's international collaboration rate. We therefore provide an institutional account of these dynamics, drawing on Stichweh's [Social Science information 35(2):327–340, 1996] original paper on international scientific collaboration, which, in examining the interrelated

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development of national and international scientific networks, predicts a transitional phase during which science becomes a more national enterprise, followed by a phase marked by accelerating international collaboration. Validating the application of this approach, we show that Stichweh's predictions, based on European scientific communities in the 18th and 19th centuries, seem to apply to the Chinese scientific community in the 21st century.

Keywords International collaboration · Diffusion · Nanotechnology · China · Indigenous innovation

JEL Classifications O33 · O38 · O31

Introduction

Bibliometric studies have been very nearly unanimous in concluding that science has globalized in two distinct ways. First, there is significant evidence that it has become more internationally interconnected. These interconnections are evident in the growth of international conferences, cross-border funding (Shapira and Wang 2010), and in the share of peer-reviewed scientific publications involving authors from multiple countries.[1] Second, research activity has become more evenly spread across countries, eroding national concentrations of scientific productivity. This diffusion[2] of scientific activity is apparent in the growing shares of emerging scientific powers in research publications, on editorial boards of journals (Braun et al. 2007) and in global patent filings (Dang et al. 2010).

The natural presumption seems to have been that the diffusion of scientific capacity should *increase* international collaboration (IC) rates by increasing the number of potential international collaborators (Wagner and Leydesdorff 2005b; Table 1). While this is in line with the available evidence, we note that these two dimensions of globalization need not always work in tandem. After all, nanotechnology research has been diffusing towards East Asia, especially to China[3]; and East Asian countries are amongst the least globally

[1] Wagner and Leydesdorff (2005a) show that the share of all SCI-recorded scientific papers that involve authors from more than one country roughly doubled, from 8.7% in 1990 to 15.6% in 2000. Using slightly different data, they show a continuation of this upwards trend through 2005 (Leydesdorff and Wagner 2008). Wagner (2008) notes that this trend is similar across many scientific disciplines. The United States National Science Board (NSB 2010) finds that international collaboration rates in social sciences, mathematics, engineering and other sciences rose from 8 to 22% between 1988 and 2008.

[2] In this paper we employ the standard term "diffusion" to describe the spread of scientific activity to formerly underrepresented countries. We do so, however, with the caveat that while some of the growth in Chinese scientific productivity can be attributed to the diffusion of knowledge to China from more scientifically advanced institutions in the U.S, Europe and Japan, some can also be attributed to China's growing efforts at "indigenous innovation," described below. The diffusion model, insofar as it connotes flows from core to periphery, does not adequately capture the complexity of China's rising share of global scientific productivity.

[3] Chinese publications have grown rapidly in quantity, whether one looks at nanotechnology only (Youtie et al. 2008), or at science in general (Kostoff et al. 2007). Indeed, the data used for the current study (described in "Data" section) show that China's nanotechnology research output (as measured by the quantity of publications in ISI-listed journals) surpassed that of Japan in 2002, and even that of the US in 2008. Robust upwards trends in the research output of other East Asian economies—particularly Japan, South Korea and Taiwan, have also been reported for some time now (Kostoff et al. 2006b).

interconnected of the major scientific powers (NSB 2010, chap. 5). It is therefore possible that successful policies in these countries to expand their scientific output could retard, or even stop, the growth of IC. Nanotechnology research is of significant interest in this regard because the field is nascent, has seen major growth in the last 20 years, and has been accorded high priority by the Chinese government (Appelbaum and Parker 2008). By studying international nanotechnology research collaborations, we are therefore able to shed light on the connections between national policies and the evolution of international scientific networks. To this end, we examine the arithmetic effects of the diffusion of nanotechnology research (as measured by publications) to East Asia, and especially to China, on the interconnectedness of the global nanotechnology research network. We do so using a large dataset that is intended to include all ISI-recorded nanotechnology publications worldwide since 1990.

International research collaboration is important. Governments around the world have provided resources and incentives to increase IC rates as a means of achieving scientific excellence.[4] There are good reasons to expect these efforts to contribute to scientific productivity and quality. First, denser international scientific networks, with strong national connections, serve to promote more rapid dissemination of scientific knowledge. Second, collaboration is believed to enhance research quality by exploiting synergies between countries with differentiated scientific capabilities (Stichweh 1996). Consistent with these expectations, internationally collaborative papers are cited more often (Glanzel 2001; Aksnes 2003), and citations are often taken as an indicator, albeit an imperfect one, of quality (Kostoff 1998; Aksnes 2006).

Given these benefits of dense international research networks, two obvious follow-up questions are why Chinese scientists do not collaborate internationally more often, and whether this is likely to change. Presuming that the IC rate reflects a scientific community's success in attracting international research partners, it can be taken as a proxy for scientific quality and maturity. Low IC rates then indicate less widespread preparedness to engage in top caliber research, while upwards trending IC rates imply scientific progress. This matters, given that the Chinese government is attempting to strengthen national scientific capacity in order to promote "Indigenous Innovation". These policies have come in for criticism, in part on the grounds that neither the political structures governing technology development nor China's scientific labor force, are adequate to the task (Breznitz and Murphree 2011).[5] The issue is also clearly important in light of a politically and commercially charged debate over the implications of Indigenous Innovation policies for technology transfer and intellectual property rights (e.g., McGregor 2009).[6] The forces driving China to engage in more IC and the constraints that hinder this process are therefore worth studying.

We engage these issues through a review of China's recent science and technology policies, and by comparing China's experience as it develops its scientific capacity with the experiences of Europe in the 18th and 19th centuries. In the latter endeavor, we draw on Stichweh's (1996) study of the history of scientific collaboration in Europe, which argues

[4] For a description of some of these efforts, see Appelbaum and Parker (2008 China); Cabinet Office of the Japanese Government (2000, pp. 48–49—Japan), and Defazio et al. (2009—European Union).

[5] There is bibliometric evidence on this. While the quantity of publications by Chinese authors grew rapidly, quality has lagged (Kostoff et al. 2006b), but has recently begun to turn around (Youtie et al. 2008); and the productivity of Chinese Science and Technology researchers is low (OECD, p. 332).

[6] Our analysis certainly will not resolve these debates. Our point here is only that the political heat generated by China's scientific surge motivates a more thorough search for the proper understanding of these trends.

that before an emergent power can engage in internationally collaborative scientific research it must first turn inward in an effort to build national scientific institutions and a core body of scientific competences. Once this is achieved, and science becomes increasingly specialized, it is "progressively improbable that relevant and necessary collegial relationships should accidentally be coextensive with national contexts" (Stichweh 1996, p. 332). Thus, he concludes, the paradox of scientific development is that "the path to modern global and universal science leads via an intermediate phase of strong *nationalization* of science" (p. 329, emphasis in original). One of the key contributions of our work is that by combining our data analysis with a review of literature on the highly specialized field of nanotechnology development, we find that Stichweh's theory has strong empirical resonance in the 21st century. China's scientific expertise has grown and has altered the development of international scientific networks, and it has done so through a period of scientific nationalization that is clearly apparent in several respects in the bibliometric data.

The paper proceeds as follows. We describe the data in the next section. The following section presents trends in national participation and IC in the nanotechnology literature. It underscores the ever-growing diffusion of nanotechnology research across countries, and contrasts it with an abrupt halt in IC rates at the turn of the 21st century. The subsequent section on "Arithmetic decomposition" adapts a decomposition framework commonly used in economic studies of structural transformation (e.g., Chenery et al. 1986), to examine the relationship between scientific diffusion and interconnectedness, emphasizing the role of China. A section titled "The Chinese experience" asks why China's IC rates have not risen. It examines the role of growth of a country's scientific community in holding down IC rates, and then reviews the policies and historical legacies that may help to explain China's rapid increase in publication, its low rate of IC, and the timing of its down and up pattern of IC. Trends in Chinese language publication are also analyzed, and all of these trends are compared with Stichweh's (1996) predictions. We end with some concluding thoughts.

Data

We chose a data collection method similar to the one in Lenoir and Herron (2009), built upon the query from Kostoff et al. (2006a). We use the query from Kostoff et al. (2006) to retrieve all relevant nanoscience and nanotechnology articles from the ISI Web of Science (WoS) database, on a country-by-country basis. The search query is presented in the Appendix.

The WoS database contains English language metadata records for over 40 million scholarly research articles, providing a convenient and rich resource for scientometric analysis of a field. Over the last decade a variety of advanced query techniques for retrieving nanotechnology-relevant documents from the WoS have been used for scientometric studies of nanotechnology. Huang et al. (2008) provide a comparison of some of the different advanced nanotechnology retrieval strategies for the ISI Wos that have been developed by Glänzel et al. (2003), Noyons et al. (2003), Porter et al. (2008), Mogoutov and Kahane (2007) and Leydesdorff and Zhou (2007). Huang et al. (2008) notes a number of early query approaches that use 'nano*' as a query term—selecting all documents that contain the four letters 'nano' in sequence anywhere in the title, abstract or keywords fields—just as with a recent nanotechnology analysis by Onel et al. (2011). Sets of exclusionary terms are used to filter query results in Porter et al. (2008), Pouris (2007) and

Mogoutov and Kahane (2007). The approach in Porter et al. (2008) uses only the SCIE database in WoS. The method in Zitt and Bassecoulard (2006), described but not evaluated by Huang, uses a keyword approach similar to Kostoff et al. (2006a) and Porter et al. (2008), adding a citation-based approach to the mix, just as the method in Onel et al. (2011). The development of a nanotechnology-specifying query in Mogoutov and Kahane (2007) starts with a method similar to Kostoff et al. (2006a), but unlike Kostoff et al., Mogoutov and Kahane refine the query using automated methods for identifying co-occurring term pairs highly specific to areas of nanotechnology, measuring the co-occurrences using what is called an index of specificity (denoted as '*I*'), a quantitative measure of how specific a word pair is to nanotechnology and/or a subfield. The query in Kostoff et al. (2006a), a basis for many of the other methods already described, provides a number of advantages for collecting nanotechnology documents from ISI: it was developed iteratively taking advantage of expert involvement in its later refinements, it uses only lexical elements thereby providing a degree of ease of implementation, and it appears to have excellent recall and precision in retrieving nanotechnology-specific documents.

Descriptive analysis

This paper employs the following definitions. *Collaborative papers* are those that list more than one author, and are of two types. *Internationally collaborative papers* list authors from more than one country, while the authors of *domestic collaborations* all come from the same country. A paper is credited to a country if one or more of its authors list an affiliation with an institution in that country. Thus, a paper is "Chinese" or "Chinese-authored" if at least one of the authors on the paper lists a Chinese institutional affiliation. Internationally collaborative papers will therefore be credited to more than one country. A paper is *East Asian* if it involves at least one author from China, Japan, South Korea, Singapore or Taiwan. An East Asian paper is internationally collaborative even if all of its authors are from among these five countries, so long as more than one country is involved. Similarly a paper involving papers from multiple countries within the EU is considered internationally collaborative.

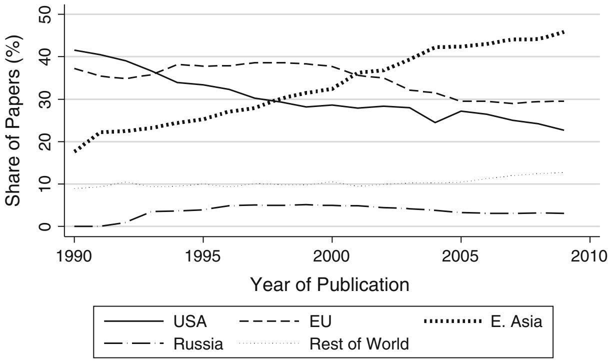
Figures 1 and 2 depict the trends in national representation in the nanotechnology literature. The shares add up to more than one due to the presence of IC.[7] To maintain a focus on the East Asian experience, Fig. 1 presents aggregate figures, while Fig. 2 splits East Asia into its five component countries. Both figures demonstrate a dramatic increase in the output share of the four relative newcomers—China, South Korea, Taiwan and Singapore, relative to that of the initial scientific powers (the United States, EU and Japan).[8]

Figure 3 plots the overall trend in collaboration, dividing collaborations into two components—those that involve purely domestic collaborations, and those that are international. It shows that the share of papers involving multiple authors grew consistently over the entire period, approaching 100% (97%) of all publications by 2009. The share of papers that involved ICs, on the other hand, grew robustly from 8.3% in 1990 to 19.6% in

[7] These shares would need to be adjusted so they add up to one if our objective were to present a sense of the changing distribution of effort or some notion of power. However, given that we are interested in international collaboration, the unadjusted figures provide a direct sense of national involvement, which will be useful for putting the growth of international collaboration rates in context.

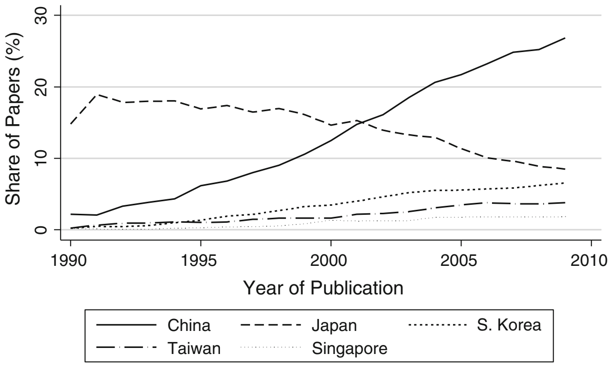
[8] It should be noted that even while the shares of papers involving the authors from the US, EU and Japan decreased, the total number of papers from each increased (not shown, in the interests of brevity).

Fig. 1 East Asia rising



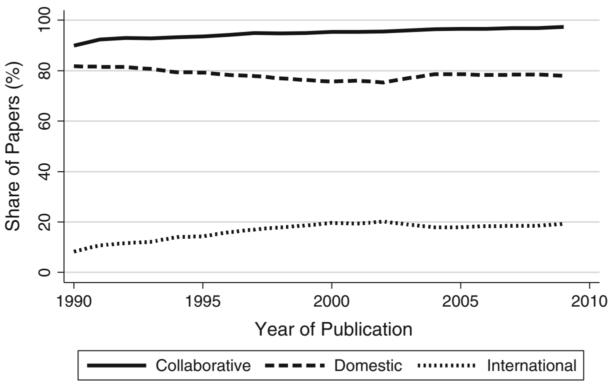
Note: Shares may add up to more than 1 due to international collaboration.

Fig. 2 Trends within East Asia



Note: Shares may add up to more than 1 due to international collaboration.

Fig. 3 Does collaboration go global?



2000, before beginning to turn downwards. It fell to 17.9% in 2005, and then recovered to 19.3% in 2009. Meanwhile, purely domestic collaborations fell from 81.7% of papers in 1990 to 75.7% in 2000, before turning around and leveling off at around 78.5%. In other words, even though the enterprise became increasingly collaborative, a large number of nanotechnologists began looking for collaborators at home starting around 2000. Figure 4 shows that the share of all collaborations involving multiple countries doubled between 1990 and 2000, but then abruptly fell, only to begin recovering again in 2005.

Figure 5 shows the percentage of papers involving each country-group that is internationally collaborative. While the figure trends upwards in all cases, IC rates in East Asia are

Fig. 4 International collaboration plateaus

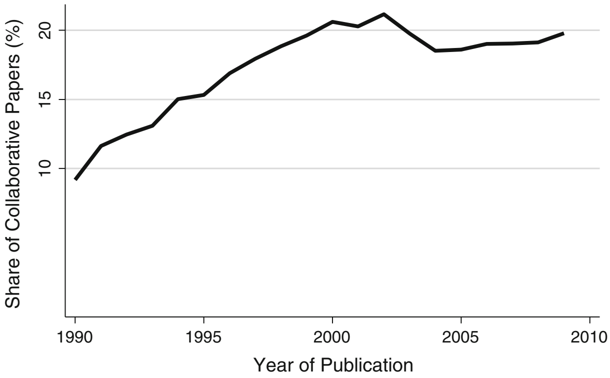
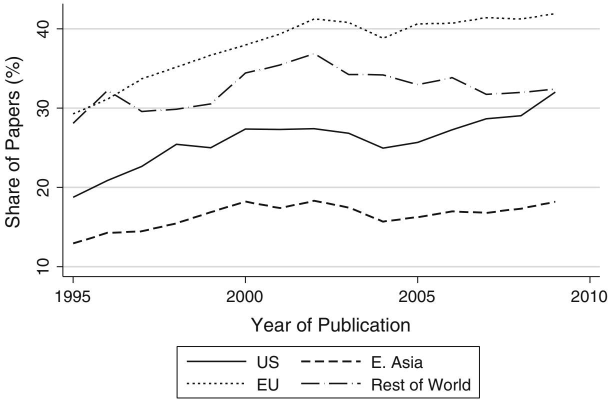


Fig. 5 International collaboration rates by Country



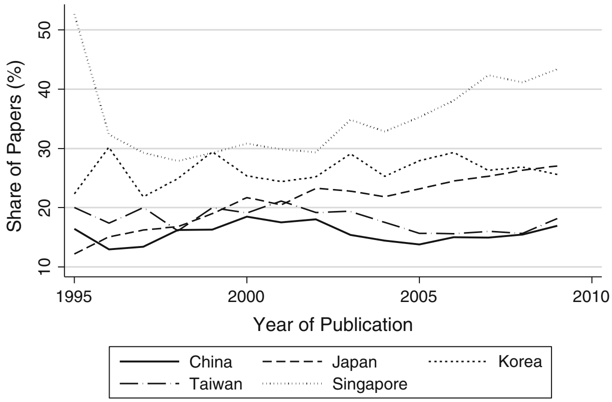
clearly much lower than those for the US and the EU.[9] Coupled with the rapid growth in East Asian publications, this suggests a possible explanation for why the aggregate IC rate leveled off: scientific output moved to East Asia, and East Asian scientists produce less internationally collaborative publications.

Figure 6 depicts IC rates for our five East Asian countries. Ignoring some turbulence in the early years when we are looking at ratios of small numbers of publications, IC rates climbed in Japan, South Korea and Singapore. On the other hand, IC rates rose until 2000 in China, before dropping sharply until 2005, and then once again recovering. The timing of these changes in China coincides with those in the aggregate trends, suggesting that trends in China may have driven the global figures after 2000, when a large share of publications involved Chinese scientists.

However, Fig. 6 also depicts a much lower rate of IC in China and Taiwan than anywhere else in East Asia. Given the dramatic growth of Chinese papers, this suggests that China's growing share of nanotechnology-related publications, rather than East Asia's share more generally, could have caused the growth in IC to pause and slightly decline after 2000.

[9] Recall that papers produced by scientists in multiple EU countries are considered internationally collaborative.

Fig. 6 International collaboration rates in East Asia



Arithmetic decomposition

To examine the relative importance of diffusion to countries with less interconnected scientists in explaining trends in IC, and also the relative importance of specific countries and regions, we now introduce a simple decomposition, adapted from approaches commonly used in economic studies of structural transformation. Let N be the number of publications in a given year, N_{Int} be the number that were internationally collaborative, N^{c} be the number with an author from country (or region) c and $N^{\sim\mathrm{c}}$ be the number without such an author, and $N^{\mathrm{c}}_{\mathrm{Int}}$ and $N^{\sim\mathrm{c}}_{\mathrm{Int}}$ be the numbers of those that are internationally collaborative. In this case, the global IC rate, λ, can be expressed as:

$$\lambda \equiv \frac{N_{\mathrm{Int}}}{N} \equiv \frac{N^{\mathrm{c}}}{N}\frac{N^{\mathrm{c}}_{\mathrm{Int}}}{N^{\mathrm{c}}} + \frac{N^{\sim\mathrm{c}}}{N}\frac{N^{\sim\mathrm{c}}_{\mathrm{Int}}}{N^{\sim\mathrm{c}}} \equiv \alpha_{\mathrm{c}}\lambda_{\mathrm{c}} + (1-\alpha_{\mathrm{c}})\lambda_{\sim\mathrm{c}}; \tag{1}$$

where α_{c} is the share of publications involving an author from country c, λ_{c} is the share of papers with an author from country c that is internationally collaborative, and $\lambda_{\sim\mathrm{c}}$ is the corresponding figure for papers without a country c author. This simply says that the global IC rate is a weighted average of the IC rates amongst those papers that involve country c and those that do not.

Next, consider the change in IC rates, $(\Delta\lambda)$, between some initial and subsequent time periods ($t = 0$ and 1). Analogously define changes over time in country c's share of publications by $\Delta\alpha_{\mathrm{c}}$, and the changes in group-wise IC rates by $\Delta\lambda_{\mathrm{c}}$ and $\Delta\lambda_{\sim\mathrm{c}}$. Define the average (over time) share of publications involving country c: $\bar{\alpha}_{\mathrm{c}} = 0.5\left(\alpha_{\mathrm{c}}^{t=1} + \alpha_{\mathrm{c}}^{t=0}\right)$; and the analogous average over-time group-wise collaboration rates $\bar{\lambda}_{\mathrm{c}}$ and $\bar{\lambda}_{\sim\mathrm{c}}$. Time-differencing (1) then yields:

$$\Delta\lambda \equiv -(\lambda_{\sim\mathrm{c}} - \lambda_{\mathrm{c}})\Delta\alpha_{\mathrm{c}} + [\bar{\alpha}_{\mathrm{c}}\Delta\lambda_{\mathrm{c}} + (1-\bar{\alpha}_{\mathrm{c}})\Delta\lambda_{\sim\mathrm{c}}] \tag{2}$$

This decomposes the change in IC rates into contributions due to diffusion and local effects. Specifically, the first term captures *diffusion effects*: changes in the IC rate due to changes in the share of papers involving country c ($\Delta\alpha_{\mathrm{c}}$). If country c's scientists are less internationally collaborative than the rest (i.e. if $\lambda_{\sim\mathrm{c}} > \lambda_{\mathrm{c}}$), and country c becomes more prolific (i.e., if $\Delta\alpha_{\mathrm{c}} > 0$) the whole term will be negative, so that the increase the in the share of papers involving country c reduces the IC rates. The terms in square brackets capture the effects of local changes in IC rates on the global IC rate. For example, if country c's scientists start collaborating less with scientists

Table 1 Decomposition analysis of the change in international collaboration (IC): the role of China

	Share of papers that involve IC			Chinese involvement			Decomposition analysis	
	1992	2000	Change	1992	2000	Change	Diffusion effects	Local effects
A. The period 1992–2000								
Chinese papers	0.171	0.185	0.014	0.033	0.125	0.092	0.016	**0.001**
Non-Chinese papers	0.114	0.198	0.084	0.967	0.875	−0.092	−0.014	**0.077**
Aggregate	0.116	0.196	**0.080**	1.000	1.000		**0.002**	**0.078**
	Share of papers that involve IC			Chinese involvement			Decomposition analysis	
	2000	2009	Change	2000	2009	Change	Diffusion effects	Local effects
B. The period 2000–2009								
Chinese papers	0.185	0.169	−0.016	0.125	0.268	0.143	0.025	**−0.003**
Non-Chinese papers	0.198	0.201	0.003	0.875	0.732	−0.143	−0.029	**0.002**
Aggregate	0.196	0.192	**−0.004**	1.000	1.000		**−0.003**	**−0.001**
	Share of papers that involve IC			Chinese involvement			Decomposition analysis	
	2000	2005	Change	2000	2005	Change	Diffusion effects	Local effects
C. The period 2000–2005								
Chinese papers	0.185	0.138	−0.047	0.125	0.217	0.092	0.015	**−0.008**
Non-Chinese papers	0.198	0.191	−0.007	0.875	0.783	−0.092	−0.018	**−0.006**
Aggregate	0.196	0.179	**−0.017**	1.000	1.000		**−0.003**	**−0.014**
	Share of papers that involve IC			Chinese involvement			Decomposition analysis	
	2005	2009	Change	2005	2009	Change	Diffusion effects	Local effects
D. The period 2005–2009								
Chinese papers	0.138	0.169	0.032	0.217	0.268	0.052	0.008	**0.008**
Non-Chinese papers	0.191	0.201	0.010	0.783	0.732	−0.052	−0.010	**0.007**
Aggregate	0.179	0.192	**0.013**	1.000	1.000		**−0.002**	**0.015**

Note Numbers in bold on the bottom row of each panel are the total change in international collaboration rates and the total changes predicted by local and diffusion effects. Numbers in bold at the end of the first two rows of each panel are the contributions to the change in international collaboration rates of Chinese and non-Chinese papers respectively

from other countries (i.e., if $\Delta\lambda_c < 0$), this will reduce the global collaboration rate, and this effect will be larger if country c's scientists are prolific (i.e. if $\bar{\alpha}_c$ is large). We refer to these shifts as *local effects*, which can be due to local trends in country c ($\Delta\lambda_c$) or elsewhere $\Delta\lambda_{\sim c}$.[10]

[10] One important caveat: By construction, all internationally collaborative papers involving country *c* enter the numerator when calculating country *c*'s international collaboration rate, and no internationally collaborative papers involving country *c* are counted towards the rest of the world's international collaboration rate. Thus, we systematically underestimate the international collaboration gap, and therefore the contribution of diffusion effects towards less internationally collaborative countries to slowing international collaboration.

Table 1 decomposes the change in IC rates across papers with Chinese authors and those without Chinese authors, while Table 2 decomposes it across those with and without East Asian authors. The first two columns contain the λs and the third, their changes. The fourth and fifth columns contain the αs and the sixth, their changes. The final two columns calculate the decomposition.

To illustrate how the decomposition works, consider the period from 2000 to 2009 (Panel B of either table), when the share of papers that are internationally collaborative shrank by 0.4% points ($\Delta\lambda = 0.196–0.192$). Now focusing on the Chinese/non-Chinese decomposition (Table 1), we note that the increase in the share of publications from China (the diffusion effect) would, on its own, have reduced the IC rate by 0.3% points, because Chinese papers are less likely to be collaborative, and more papers came to have Chinese

Table 2 Decomposition analysis of the change in international collaboration (IC): the role of East Asia

	Share of papers that involve IC			Share of papers E. Asian			Decomposition analysis	
	1992	2000	Change	1992	2000	Change	Diffusion effects	Local effects
A. The period 1992–2000								
E. Asian papers	0.110	0.182	0.072	0.253	0.324	0.071	0.010	**0.021**
Non-E. Asian papers	0.118	0.203	0.086	0.747	0.676	−0.071	−0.011	**0.061**
Aggregate	0.116	0.196	**0.080**	1.000	1.000		**−0.001**	**0.082**
	Share of papers that involve IC			Share of papers E. Asian			decomposition analysis	
	2000	2009	Change	2000	2009	Change	Diffusion effects	local effects
B. The period 2000–2009								
E. Asian papers	0.182	0.182	0.000	0.324	0.459	0.135	0.024	**0.000**
Non-E. Asian papers	0.203	0.201	−0.002	0.676	0.541	−0.135	−0.027	**−0.001**
Aggregate	0.196	0.192	**−0.004**	1.000	1.000		**−0.003**	**−0.001**
	Share of papers that involve IC			Share of papers E. Asian			Decomposition analysis	
	2000	2005	Change	2000	2005	Change	Diffusion effects	Local effects
C. The period 2000–2005								
E. Asian papers	0.182	0.162	−0.020	0.324	0.424	0.100	0.017	**−0.007**
Non-E. Asian papers	0.203	0.192	−0.011	0.676	0.576	−0.100	−0.020	**−0.007**
Aggregate	0.196	0.179	**−0.017**	1.000	1.000		**−0.003**	**−0.014**
	Share of papers that involve IC			Share of papers E. Asian			Decomposition analysis	
	2005	2009	Change	2005	2009	Change	Diffusion effects	Local effects
D. The period 2005–2009								
E. Asian papers	0.162	0.182	0.019	0.424	0.459	0.035	0.006	**0.009**
Non-E. Asian papers	0.192	0.201	0.009	0.576	0.541	−0.035	−0.007	**0.005**
Aggregate	0.179	0.192	**0.013**	1.000	1.000		**−0.001**	**0.014**

Note East Asia is China, Japan, South Korea, Taiwan and Singapore authors. Thus, three-quarters of the reduction in IC over this period is due to the spread of science from more collaborative countries to China. The increased diffusion of science to East Asia (Table 2) has around the same effect as diffusion to China does. We emphasize that, by construction, this figure is an underestimate of the contribution of diffusion to the reduction in collaboration rates.

The remaining reduction in IC rates during 2000–2009 is due to local effects. Chinese collaboration rates dropped by 1.6% points, which, on their own, would have caused collaboration rates to fall a further 0.3% points. However, non-Chinese collaboration rates rose by 0.3% points, lifting the global collaboration rate by 0.2% points. Absent this increase in IC elsewhere, global collaboration rates would have dropped 0.6% points for reasons owing to China.

The situation in the 1990s (1992–2000), when the US and EU dominated nanotechnology, is almost the opposite (Panel A of either table). IC rates rose 8.0% points from 11.6 to 19.6%, which is accounted for almost entirely by an increase in IC rates amongst non-Chinese scientists (7.7 out of the 8.0% points), and amongst non-East Asian scientists (6.1 of the 8.0% points).

These "long-difference" results therefore reveal an important tension. Science globalizes in two different ways—by shifting to other countries where scientific productivity (at least as measured by SCI-indexed publications) is increasing more rapidly, and by becoming more internationally collaborative. The two trends seem to have worked in opposing directions: as nanotechnology research diffused eastwards, international connectivity in the scientific community actually declined. We have shown that this was in part because East Asian research, and Chinese research in particular, was not as internationally collaborative as research produced with U.S. and European involvement. This said, we also note a deceleration in IC amongst non-Chinese scientists in the latter decade.

Finally, to examine shorter-term trends, Panels C and D of the two tables decompose the shifts during 2000–2005 and 2005–2009. In contrast to the long-term trends, changes over these shorter spans are driven mainly by local effects, although diffusion to China continues to play a role. Particularly noteworthy are the larger fluctuations in IC rates amongst Chinese papers. Fluctuations in Chinese IC rates can account for 0.8 out of the 1.7% point decrease in IC rates during 2000–2005, and 0.8 out of the 1.3% point increase during 2005–2009.

The Chinese experience

We have demonstrated that the shift of nanotechnology research to East Asia, and to China in particular, caused IC rates in nanotechnology research to decelerate. This occurred because papers involving East Asian authors, especially Chinese authors, were much less likely to be internationally collaborative. However, global IC rates dipped and then recovered between 2000 and 2009. This is due, arithmetically, to a dip and subsequent recovery in China's IC rate. We now turn to a brief discussion of what might be behind the generally low rate of IC in China, its decline during 2000–2005 and its subsequent increase. This may shed light on whether a continuing shift of research to China is likely to have a long-term dampening effect on IC.

The role of size

One possible reason why China's IC rate did not rise significantly over time, and why non-Chinese IC rates decelerated, is that these scientific communities grew, and that the

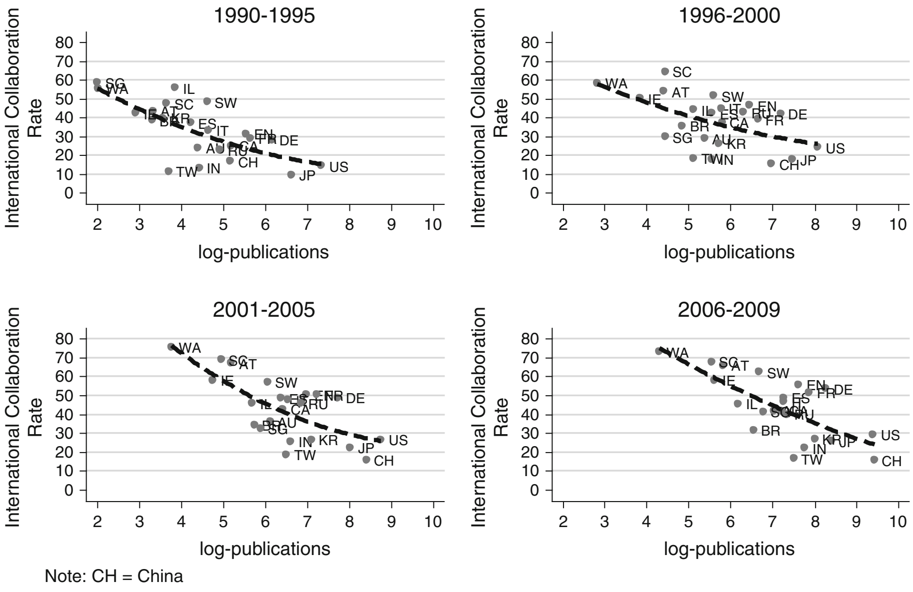


Fig. 7 More prolific countries collaborate less

probability of finding a suitable collaborator at home is likely to grow with the pool of potential collaborators. Figure 7 begins to examine this possibility for four half-decades. Taking the number of publications from each country as our proxy for the size of the effective nanotechnology research community,[11] it shows that larger communities do indeed have lower IC rates—the lines of best fit in each panel slope downwards. This said, there is clear evidence of countervailing time trends—even though communities of nanotechnologists in each country grew dramatically in all countries, IC rates rose for almost all countries. China is the standout exception in this regard. China's IC rate was not only smaller than expected given its research output, it was essentially stationary over the longer term. Moreover, other prolific countries' IC rates increased, even while they grew.

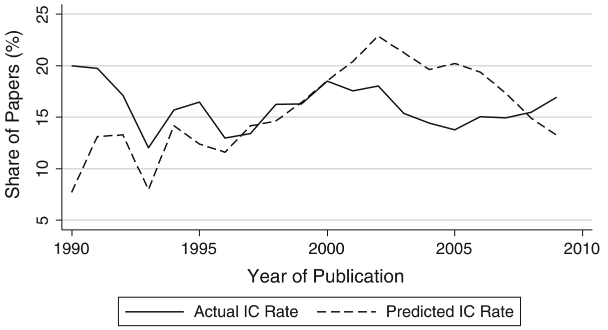
Figure 7 clearly demonstrates a lower proclivity for IC in China. What remains less clear is whether the especially dramatic growth of China's research output can explain why its IC rates did not rise while other countries' IC rates did. To examine this possibility, we turn to regression analysis and out-of-sample prediction. We begin by regressing IC rates on the log-number of publications, allowing for fixed effects for each year and country in our sample. Denoting countries by c and years by t, we estimate:

$$\mathrm{ICR}_{\mathrm{c},t} = \sum_{\mathrm{c}} \alpha_{\mathrm{c}} D_{\mathrm{c}} + \sum_{t} \delta_t D_t + \sum_{k=1}^{K} \gamma_k \left[\ln\left(\mathrm{output}_{\mathrm{c},t}\right)\right]^k + e_{\mathrm{c},t} \tag{3}$$

The first term on the right hand side captures time-invariant country effects (D_{c} is a dummy variable indicating that country c's IC rate is being considered); the second term captures country-invariant time effects. The next summation allow for a polynomial, degree-K relationship between (logged) output and IC. We take logs of output in order to prevent the regression results from being driven by trends in the most and least prolific countries, and

[11] Estimates of the number of nanotechnology researchers by country and year seem to be unavailable.

Fig. 8 Actual versus predicted international collaboration rates in China



use a polynomial specification to allow for a non-linear relationship between output and IC. Both the adjusted R-squared and the Akaike Information Criterion recommend that IC rates be modeled as a fifth-degree polynomial in log-output (i.e. $K = 5$).

Given our interest in using out-of-sample prediction to explore Chinese exceptionalism, we conduct this regression on a sample that excludes China. Our estimates of $\gamma_1, \ldots, \gamma_5$ indicate that IC rates fall with output over the entire range of observed output levels. Coefficients on the year-dummies (δ_t, not shown for brevity) indicate a rising global tendency towards IC rates through our sample period. Thus, the predictable trends in IC rates outside China arise from a tension between growing national scientific communities (which drives down IC rates), and some generalized global trend towards greater IC (perhaps due to improvements in communication technology, growing specialization within nanotechnology, or the increasing importance of costly specialized equipment).

Next, we combined the estimated effects of time and output on IC rates with the observed Chinese output levels to predict a time path for China's IC rates. We then translated this predicted series of IC rates upwards so that the predicted and actual rates in the year 2000 coincide. The actual and predicted time path of IC can then be compared in Fig. 8. A fair characterization of these results appears to be that while the regression does predict some short run movements in Chinese IC rates, it does an extremely poor job in two respects. First, it predicts a far more rapid increase in China's IC rates prior to 2002 than was observed. Second, it predicts a decline in IC between 2002 and 2009 that *accelerates* in 2005, whereas IC rates in fact began to fall in 2000, and the decline was reversed in 2005. This discrepancy in the predicted and actual dynamics of IC rates (despite corrections for time and country fixed effects) suggests a substantial role for country-specific, time-varying forces, such as the effects of shifting national science policy and receding national constraints on IC. These time-varying, Chinese forces should explain why collaboration rates grew so little early on, and why they began to rise after 2005, even as the growth of Chinese scientific output accelerated.

A brief institutional history of Chinese science and technology policy

The Cultural Revolution effectively shut China's university system down for several years (1966–1976), resulting in significant and long-lived damage to China's scientific capacity—one cohort of scientists was persecuted and a decade's worth of future scientists were not produced. The resulting shortage of scientific talent has constrained China's scientific advancement, and alleviating these constraints has been a central policy concern (Simon and Cao 2009).

In the late-1990s, China committed itself fully to a program of modernization and economic growth based on aggressive public investment in science and engineering education, infrastructure for support of applied research and development. Several key policies designed to grow China's talent pool of scientists and engineers were implemented in the 10th Five-year plan (2001–2005) to boost innovation capacity in strategic high-tech fields and to achieve "leap-frog" development. Nanotechnology and biotechnology were explicitly targeted as areas of strategic growth in the plan. The scale of China's program of investment in science and engineering education during this and the 11th Five-Year Plan (2006–2010) was impressive, particularly when absolute numbers of new researchers and R&D personnel are taken into consideration. Between 2001 and 2008 the total number of R&D personnel in China more than doubled, increasing by 113% from around 750,000 to 1.6 million R&D personnel. This represented an average annual growth of 11.6%, well exceeding the growth in R&D personnel by the US, Japan and the EU nations. With 1.6 million scientist and engineer full-time equivalent researchers in 2008, China surpassed the United States (NSB 2012).

Despite this impressive growth of R&D personnel in China, there are still serious problems with the quality of these recent cohorts in comparison with other advanced industrial economies. Missing from the current mix is an educational system that discards rote learning and instead promotes creativity, as well as an S&T environment that supports the creative risk-taking that can lead to indigenous innovation. Across the board in industry R&D as well as state and university research labs, mid-career level leadership is needed to manage and lead the impressive numbers of newly minted Chinese S&T workers to innovative discoveries and path breaking inventions. Without a culture that supports these key ingredients of entrepreneurial behavior it will be difficult to "leapfrog" beyond incremental improvements in existing technologies or technologies imported through foreign domestic investments (OECD 2008; Simon and Cao 2009).

The Chinese Ministry of Science and Technology (MOST) and the Chinese Academy of Sciences (CAS) have been sensitive to these problems and have taken measures to increase the quality of Chinese researchers and breach the leadership gap. Several of the policies directly relevant to the argument posed in this paper are ones that aim to stimulate IC and publication. For instance, to ensure that the quality of Chinese researchers is on a par with researchers of other leading S&T nations, doctoral students are now expected to publish at least one article in a journal listed in Thomson's Science Citation Index; for more experienced academics, publication records are increasingly used to determine funding; and a series of programs have aimed at persuading foreign-educated Chinese scientists to return home. These efforts to improve the quality of Chinese researchers have resulted in the Chinese science system becoming better connected internationally (OECD 2008). Another policy intended to stimulate innovative leadership skills, implemented in the 10th Five Year Plan (2001–2005) and continued in the 11th Five Year Plan (2006–2011), is an international cooperation fund through which foreign research institutions are invited to submit funding proposals jointly with Chinese researchers and institutions. By working with highly successful international teams, the goal of the policy is to bring Chinese researchers into contact with leadership skills that can be absorbed and transplanted to the Chinese research community. Another measure intended to stimulate creativity and innovation is the revised Law of Science and Technology Progress implemented in 2007, which encourages S&T personnel "to explore and innovate freely, and shoulder risks bravely: they will not be penalized for failing to achieve their goals in high-risk research if they can prove that they have tried their best" (Simon and Cao 2009).

These skill-development policies were accompanied by serious efforts at institutional development with a view to building national capabilities in specific scientific areas directly relevant to our argument (Bai 2005; Appelbaum and Parker 2008, 2012a, 2012b). National research institutes were expanded rapidly and given mandates and funding to target specific scientific disciplines and areas. Science parks that similarly focused on specific scientific areas were planned and built. Funding was ramped up, often through new funding programs targeted at specific disciplines and areas. China issued its fifteen year Medium and Long-Term Plan for the Development of Science and Technology 2006–2020 (hereafter, MLP), which called on China to develop "indigenous innovation" in hopes of achieving "technological leapfrogging"—moving directly into high-impact emerging technologies, thereby becoming less dependent on technology transfer from foreign firms. The MLP called for China to invest heavily in research and development in advanced technologies, in order to become an "innovation-oriented society" by 2020 and a world leader in science and technology by 2050. The MLP targeted nanotechnology as one of four science mega-programs for funding. Both the 11th and 12th Five-Year Plans (2006–2010, 2011–2015) also view innovation as key to solving China's economic, social, environmental and national security challenges with nanotechnology in the group of top priorities. In addition to making resources available for science and technology research, one explicitly identified objective of these policies was the reform of the science and technology system itself (Appelbaum and Parker 2008, 2012a, 2012b).

Thus, despite the weak starting position, there was a massive effort to develop national scientific institutions and capabilities. Moreover, scientific differentiation was clearly an objective and outcome of these efforts.

China's (temporary) inward turn

Noting that China is not the first scientific power to emerge on the international stage, we now attempt to put these institutional trends into a longer historical context. We are guided in this discussion by the theoretical perspective of Stichweh (1996), which he formulates based on the historical development of European scientific communities in the 18th and 19th centuries. As discussed in the introduction, Stichweh argues that growing scientific interconnectedness is, paradoxically, the result of greater scientific nationalism. To resolve this paradox, he begins by noting that national scientific institutions develop by making science more inclusive. This inclusiveness is achieved through an expansion of research institutes and an increased emphasis on science in the mission of educational institutions. The personnel demands of this shift are met through growth and democratization of the national scientific community. Growth in the scientific community in turn facilitates the development of local research networks. These networks naturally develop local disciplinary specializations. Greater specialization and a growing scientific community require a wider range of research outlets. Moreover, this new, more inclusive, national science community requires and supports more national mediums of communication. New, specialized journals therefore develop, many of which are in the national language or are bilingual. These journals help to bridge linguistic gaps between national and international research networks. Thus, there is a phase in which science turns inwards as national scientific networks become more important than international ones. Meanwhile, specific geographic locations become sites for the penetration of international science into national scientific information and communication networks. As this national institutional development leads to greater scientific capacity in specific areas, the gains to IC increase and connections with the international scientific community thicken once more.

The previous subsection of this paper shows that, despite China's weak starting position, there was a massive effort to develop national scientific institutions and capabilities. Moreover, scientific differentiation was clearly an objective and outcome of these efforts. However, in contrast to the European experience that Stichweh's theory draws upon, China's scientific development and differentiation process was both state-led, and more geared towards the applied sciences (Kostoff et al. 2007). Notwithstanding these differences in the forcing process, the end result appears to have been a transition, wherein national scientific development leads to greater international interconnectedness via a brief but obvious phase in which Chinese science turns inwards. Moreover, this transitional inward turn is manifest in each of the specific ways Stichweh's theory anticipates.

First, the Chinese scientific community did grow around these national institutions. For example, Kostoff et al. (2006b) find that their list of the most highly cited first authors in nanotechnology includes almost as many Chinese as US scientists. They also report that in terms of sheer output, the top Chinese institutions surpass the top US and European institutions.

Second, policies targeting the development of expertise in specific scientific areas did result in a differentiation of Chinese science. The surging share of nanotechnology output from China that we have documented points to this, and data presented in Kostoff et al. (2007) show that China has acquired a distinct focus and international presence in the physical and engineering sciences.

Third, as China's science and technology system became more inclusive, the scientific community turned inward in search of collaborators. Indeed, we have shown that China's IC rate in nanotechnology research dropped by almost a third in five years (Fig. 6).

Fourth, there was an inward turn in terms of language as science was democratized. Figure 9 looks at the English language publication rates of those prolific countries in which English is not the dominant language. Outside China, English language rates climbed steadily, to over 98% by 2009. Chinese rates, on the other hand declined from 92% in 1997 to 81% by 2002, before beginning to recover. Thus, English is used less in Chinese publications and its use declined as the university system expanded. Both findings are consistent with the notion that an expanding and democratizing scientific community, constrained by its past, brought a large number of new scientists into the fold who were either unable to read or write scientific articles in English, or preferred not to do so. Lin and Zhang (2007), whose data identify authors, show that many Chinese authors publishing nanotechnology articles in Chinese can and do publish in English as well. These authors would not require scientific results to be communicated in Chinese. Lin and Zhang therefore go on to provide anecdotal evidence to support the hypothesis, consistent with our conclusions, that it is a *distinct* community of relatively young and relatively old scientists who lack the English language skills to participate in science in English, which supports the development of Chinese language journals.[12]

Fifth, also in line with Lin and Zhang's hypothesis, the set of journals publishing Chinese language papers grows and then contracts, and also becomes more bilingual during its growth phase (Fig. 10). These trends are also suggestive of Stichweh's argument that publication in the national language is largely transitional, and part of an organic shift in the linguistic capabilities and preferences of a growing national scientific class. Ren and

[12] This trend towards Chinese language publication is not limited to nanotechnology (e.g., Valkimadi et al. 2009).

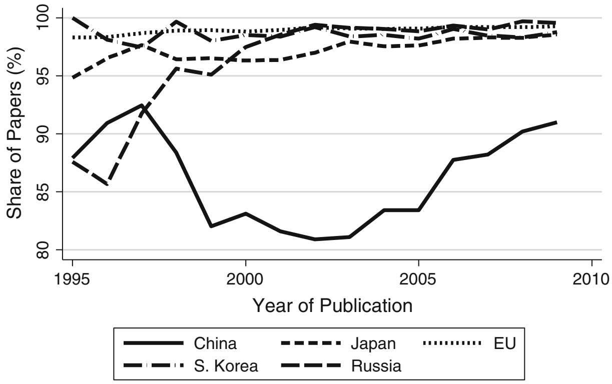
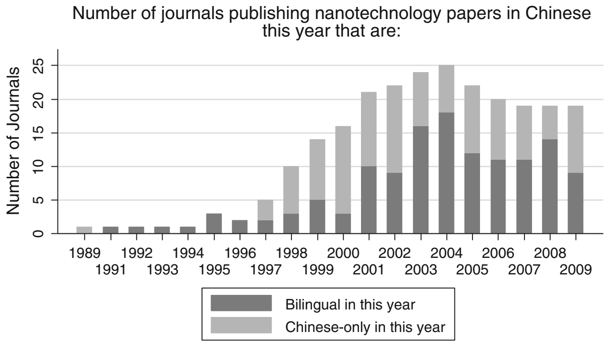


Fig. 9 Share of papers written in English



Note: Included journals are those that published at least one Chinese language paper (other than an editorial) in that year. A journal is bilingual if it also published at least one non-Chinese paper in that year.

Fig. 10 Did Chinese language papers appear in Chinese-only or in bilingual journals?

Rousseau (2002) note that many Chinese scientific journals, not limited to nanotechnology, publish articles with translated abstracts, similarly suggesting an attempt to bridge internal and international scientific networks.

Sixth, specific geographic areas did become sites for the penetration of international science. Tang and Shapira (2011) provide compelling bibliometric evidence using an index of revealed comparative advantage, of large variations in the intensity of IC between regions. Hong Kong and Beijing are particularly successful at IC, Shanghai is somewhat average, and some regions, including Anhui and Hubei, remain relatively inward looking despite having significantly increased their presence in the nanotechnology literature.

While all of these trends are anticipated by Stichweh's theory during a transitional phase of national scientific development, the theory also forecasts increasing interconnectedness once a differentiated set of national capabilities is developed. This too is suggested by our data. We have already documented that the English language publication collaboration rate of Chinese scientists turned back up, and that their rising IC rate lifted IC rates globally. This resonance with a set of theoretical predictions that are rooted in historical analysis provides significant comfort that scientific collaboration will continue to grow. These international networks will be increasingly dominated by countries in East Asia, and their growth will not always be smooth, but they appear likely to thicken for the foreseeable future.

Conclusion

As Liu et al. (2011) have shown, China's leaders have long been concerned with innovation, beginning as far back as 1978, when Deng Xiaoping decreed that intellectuals were part of the working class, and S&T constituted a "productive force" and therefore a key to China's "Four Modernizations" drive. In 1999 the Communist Party Central Committee and State Council:

> …issued the "Decision on Strengthening Technological Innovation, Developing High Technology and Realizing Industrialization," calling for the construction of a national innovation system and speeding-up of the industrialization of the S&T Achievements…. This period (1995–2005) is marked by the introduction of the concept of "innovation" into China's discourse, and thereby the expansion of China's innovation policies beyond S&T and industrial policies (*Ibid.*, 920, 922).

China's National High-Tech Research and Development Program (known as the 863 Program) had been adopted as early as 1986; the National Basic Research and Development Program (known as the 973 Program) was similarly implemented in 1997. These efforts to prioritize innovation culminated in the MLP, with its emphasis on indigenous innovation and techno-nationalist aspirations.

We find it interesting that China resumed its outward turn towards IC at around the same time it was significantly ramping up these efforts at innovation. While the U.S. Chamber of Commerce (McGregor 2009) and the U.S.–China Economic and Security Review Commission (2010) view these efforts as excessively nationalistic,[13] we simply note that there may be a tension between the nationalist aspirations for technological supremacy on the part of governments, and the desire (indeed, need) of scientists for IC, on which the advance of highly specialized science depends.

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Appendix

Nanotechnology-specific query terms (Kostoff et. al 2006a)

‘‘NANOPARTICLE* OR NANOTUB* OR NANOSTRUCTURE* OR NANOCOMPOSITE* OR NANOWIRE* OR NANOCRYSTAL* OR NANOFIBER* OR NANOFIBRE* OR NANOSPHERE* OR NANOROD* OR NANOTECHNOLOG* OR NANOCLUSTER* OR NANOCAPSULE* OR NANOMATERIAL* OR NANOFABRICAT* OR NANOPOR* OR NANOPARTICULATE* OR NANOPHASE OR NANOPOWDER* OR NANOLITHOGRAPHY OR NANO-PARTICLE* OR NANODEVICE*OR NANODOT* OR NANOINDENT* OR NANOLAYER* OR NANOSCIENCE OR NANOSIZE* OR NANOSCALE* OR ((NM OR NANOMETER* OR NANOMETRE*) AND (SURFACE* OR FILM* OR GRAIN* OR POWDER* OR SILICON OR DEPOSITIONOR LAYER* OR DEVICE* OR CLUSTER*

[13] For a review of some of these concerns, see Appelbaum and Parker (2012b).

OR CRYSTAL* OR MATERIAL* OR ATOMIC FORCE MICROSCOP* OR TRANSMISSION ELECTRON MICROSCOP* OR SCANNING TUNNELING MICROSCOP*)) OR QUANTUM DOT* OR QUANTUM WIRE* OR ((SELF-ASSEMBL* OR SELF-ORGANIZ*) AND (MONOLAYER* OR FILM* OR NANO*.

OR QUANTUM* OR LAYER* OR MULTILAYER* OR ARRAY*)) OR NANO-ELECTROSPRAY* OR COULOMB BLOCKADE* OR MOLECULAR WIRE*''.

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