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Cities and the geographical deconcentration of scientific activity: A multilevel analysis of publications (1987–2007)

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Abstract

Most current scientific policies incorporate debates on cities and the geographic organisation of scientific activity. Research on 'world cities' develops the idea that interconnected agglomerations can better take advantage of international competition. Thus, the increasing concentration of activities in these cities at the expense of others could be observed by certain scholars using measures based on scientific publications. Others, however, show that an opposite trend is emerging: the largest cities are undergoing a relative decline in a country's scientific activities. To go beyond this seeming contradiction, this paper provides a global analysis of all countries with papers in the Web of Science over the period 1987–2007. The author's addresses were geocoded and grouped into agglomerations. Registering of papers was based on the fractional counting of multi-authored publications, and the results are unambiguous: deconcentration is the dominant trend both globally and within countries, with some exceptions for which explanations are suggested.

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Introduction

The question of the contribution of cities to world science is a growing concern for both science studies and urban research. For years, science studies have focused on the analysis of the differences between countries, but recently there has been growing interest in regions and cities (Bornmann and Leydesdorff, 2011; Bonaccorsi and Daraio, 2005; Hoekman et al., 2010; Leydesdorff and Persson, 2010).

Urban geographers have focused on the role of global cities and their contribution to the globalised scientific system. Since the 1980s, the role of 'world cities' as command centres of a world-system has stirred debate in urban studies; debate that has recently been fuelled by a special issue of this journal (Derudder et al., 2010). In particular, the role of world cities as innovation and scientific centres has been studied (Matthiessen and Schwarz, 1999; Matthiessen et al., 2010; Sassen, 2001). Using a bibliometric approach and focusing on the upper level of the hierarchy of scientific places, Matthiessen and his co-authors (2010), state that the 30 largest scientific centres in the world saw their predominance increase between 1997 and 2005: 'Total growth has been 28 per cent and growth in the top 30 cities has been 34 per cent, which demonstrates a concentration process' (Matthiessen et al., 2010: 1883). This process would be concomitant to the concentration of other 'metropolitan' functions.

However, this hypothesis of an increased concentration of scientific activities has been called into question by deconcentrating trends identified by authors such as Zhou et al. (2009). They demonstrated that the growth of higher education in China is accompanied by a decentralisation of activities between the country's different regions. Another study, based on patents (Hong, 2008), also suggests that as Chinese scientific activity develops, the initial geographic concentration decreases. As the world's second largest contributor to scientific activity, China is a striking counter example to the theory of the growing concentration of scientific activity in global cities (measured by publications).

In order to better understand the issue and perhaps explain this contradiction, we have studied the long-term evolution of scientific activity between countries, and between agglomerations at both the national and international level. It is well established that internationally, scientific activity is currently more evenly distributed between countries than in the past (Huang et al., 2012). Barely 30 years ago, the bulk of scientific production was localised in a limited number of zones (North America, Europe, Japan); since, its geographic concentration (as measured through publications) has steadily diminished. Thus, the number of countries needed to account for 80% of world publications identified by the Science Citation Index Expanded (SCI-Expanded) was 7 in 1978, 10 in 1988 (including the USSR), 13 in 1998 (with a united Germany and Russia separated from other former USSR countries), and 16 in 2008. The growth in the total number of countries that greatly contribute to the volume of world scientific publications is not the result of a decline of countries with long-standing scientific traditions; the latter continue to increase production, albeit at a moderate pace. Rather, this growth is the consequence of the rapid rise of 'new countries' in the landscape of international science. In 2008, China took the lead of these new producers when it became the country with the second highest number of publications (in natural sciences and technology); with the USA maintaining its top rank. Scientific activity has slowly spread internationally over the past 30 years, with 'old countries' (notably the USA) losing their hegemonic position, while new actors of increasing importance emerge: China in the lead, followed by South Korea, Brazil, Taiwan, Spain, to name only a few. It is not our intention to explain this phenomenon, which has been widely commented on by other authors and which is essentially rooted in the economic development and structural changes undergone by each country. The evolution of GDPs over the last 30 years is certainly an important factor, as is the development of urbanisation in certain emerging countries, and policies of higher education and research.

All this strongly suggests that changes in city ranking within the world scientific system (the emergence of Beijing, Shanghai, Hong Kong, and Seoul among the top publishing cities in the 2000s) depend more on country dynamics than on specific advantages ascribed to the world's major cities.

Our paper furthers debate by reconsidering two major methodological issues: first the definition of relevant spatial entities at city level and second, the use of a refined indicator for publications. For the former, we have geocoded all the addresses of the SCI-Expanded and designed a method for systematically grouping them into urban areas (cities/agglomerations). For the latter, we have used fractional counting of multi-authored publications to avoid the classical bias of bibliometric studies, namely double counts.

Our objective in this paper is not to discuss the theory of of global cities in general but to analyse the evolution over time of the spatial distribution of scientific activities as measured through the production of scientific papers. We also aim at analysing the changing place of global cities and agglomerations in this process.

Using this methodology, we demonstrate that at the world level, publications are not more concentrated in a selected group of agglomerations; on the contrary, the global trend is towards deconcentration. The analysis of the most contrasted changes – urban areas whose shares fluctuated the most – highlights the national developments that underpin those of the cities, notably the rapid growth in SCI-Expanded data of Asian publications (China, South Korea, Taiwan) and emerging countries (Brazil, India, etc.) and the relative decline of the countries that have figured in these lists for the longest time. We therefore carefully examined emerging trends at the country level. To better understand the process of deconcentration, we also studied what happens within each country. By selecting a number of countries that are home to those cities most represented in the data base, a deconcentration trend emerges in most countries. We shall also see that the deconcentration process takes on different forms depending on whether the country is currently expanding scientifically or if it is more stable; whether this process has benefited major, secondary hubs or rather multiple small cities.

Methodology

Our analysis is based on Thomson Reuters' Science Citation Index Expanded data base. This bibliographic data base lists publications (articles, notes and reviews) from 'leading, international scientific and technical journals'; that is to say, those that are overall the most cited by researchers themselves. It covers the fields of physics, chemistry, mathematics, biology (fundamental and applied), biomedical research and medicine, space and earth sciences, and engineering sciences. In 1987, it indexed almost 500,000 publications; the total exceeded 1 million in 2007.

Since the SIC-Expanded data base includes the institutional affiliations of all authors, it is possible to attribute papers to countries as well as to cities. Creating spatial statistics of scientific publications involves two types of choices; the first involves how publications are counted, the second the regrouping of addresses in urban areas.

Counting publications by spatial entities: The fractioning of publications

Choosing a counting unit must take into account the fact that most publications have multiple authors, grouped by affiliations, whose addresses often refer to different cities as well as to different countries. Each publication can thus be attributed to several geographical areas, which poses problems such as multiple counts for the same publication.

Moreover, it is well known that counting non-fractioned articles favours large cities because of their involvement in more interregional and international collaborations (Luukkonen et al., 1992). Another possible approach consists of taking into account only the first author, which has the advantage of assigning a unique address to each article. Naturally, this method poses problems because signing practices vary highly from field to field.

In order to avoid these issues, we chose the fractional counting of publications. In the case of a paper co-signed by authors from two different cities, each city is credited with half of the publication. We can therefore simultaneously add up totals and retain the relationship to the actual number of publications, since the sum total of all fractions would be the total number of publications worldwide.

We consider the method of fractional counting to be the most rigorous. Note, however, that the results presented in this paper were tested using three distinct counting methods (full papers, first author, fractioned papers).

Building agglomerations: Combining criteria

The scientific 'localities' determined constitute the most accurate publishing points that our geographic coding method allows us to localise. This is the smallest unit of tracking possible using the SCI-Expanded 'address' field. However, the level of precision obtained varies considerably between cities and countries. This is due to the fact that generally, the mailing address contained in this field corresponds to the municipality where the research organisation is located. The size of this spatial entity can vary considerably from one country to another depending on the degree of administrative fragmentation. Consider the following three examples: researchers in Moscow laboratories work in a very large municipality (1000 km^2) and their address thus refers to a single city, Moscow. In comparison, Parisian researchers work in a highly fragmented administrative space. Their professional address could be the city centre of the agglomeration, i.e. Paris (only 100 km^2), but it could also be one of the hundreds of municipalities that are included within the greater Paris area. Furthermore, many scientific centres are located outside the (relatively small) commune of Paris. The most important scientific localities around central Paris are Orsay, Gif-sur-Yvette, Palaiseau, Villejuif, Créteil, Châtenay-Malabry. In 2008, they produced 3426 publications, while the city of Paris produced 7561 papers. The combined total for the Paris urban region is then almost 11,000. Another typical example is the Washington DC urban area. In a compact area of several dozen square kilometres, much smaller than the municipality of Moscow, there are three major centres: the city of Washington DC itself (2500 publications), which ranks right behind the major research centre of Bethesda (3178), with College Park lagging behind (1236). It is therefore essential to construct roughly comparable urban entities if we wish to give some substance to the notion of 'scientific cities' and analyse their changing positions within the system of world science.

Figure 1 shows that regrouping scientific localities into bigger entities (examples: Paris and Washington) helps to grasp and measure scientific activity at the level of comparable metropolitan entities.[1]

How can publishing entities be regrouped within urban entities based on uniform criteria for every country in the world? Our aim was to produce universal criteria, and not divisions corresponding to a juxtaposition of national criteria (for example, using Metropolitan Statistical Areas (MSAs) for the USA, urban areas in France, etc., and then comparing the results). We confronted different global data sets, all of which are open access; certain provide land occupation data, such as ESA Iona GlobCover or Global UrbanExtent (for the latter: see Schneider et al., 2009, 2010), whereas others focus on population densities. Data from land artificialisation are not sufficiently discriminating. This holds particularly true in continuously constructed coastal areas (often designed for tourists), which does not necessarily correspond to year-round, continuous human occupation, nor necessarily dense inhabitation, and even less likely to harbour areas of scientific activity.

Using data on population density (highly fine-tuned raster data) is more convincing. There remained nevertheless problems in certain parts of the world with very high population density (the denser parts of China, The Netherlands, the Rhine-Ruhr urban area), where the standard operating thresholds did not easily isolate the real urban cores. Therefore, the best approach was to use an indicator to spatially determine strong variations in density, in order to produce a usable delimitation of urban areas. Among the *Local Indicators of Spatial Association*, we chose the local Moran's I values that identify significantly dense nuclei (Anselin, 1995). Processing density data leads to a homogeneous criterion for major conurbations. For smaller urban entities, a simpler criterion of distance (a threshold of 40 km between two localities producing publications) allowed us to identify 'small' scientific cities.

Deconcentration of publications in all the cities in the world

A simple way to evaluate concentration is to calculate the proportion of world publications produced by a given number of productive cities, say the top 10, the top 20, the top 100, etc. (Table 1). The results clearly indicate a generalised trend towards decentralisation between 1987 and 2007: the percentage of publications written by researchers from the 'top' cities has decreased over time, regardless of the city list considered (top 10, top 20, or top 30...).

In order to better understand the evolution of the most productive cities, we focused on the trajectories of cities ranked among the top 30 in 2007.

The proportion of world publications by the 25 cities ranked among the top 30 in both 1997 and 2007 regressed by 3.7 percentage points. Unsurprisingly, the share of newcomers (absent from the top 30 in 1997 and present in 2007) increased by 1.1 percentage points. The share of the five other agglomerations (present in 1997 and absent in 2007) regressed by 0.7 percentage points during the same period. Interestingly enough, the share of all other cities registered in our data base (not included in the top 30) increased by 3.3 percentage points.

This paper has focused on the evolution of the shares of each group of cities – top 10, top 20, etc. (in percentage of total publications). We have also computed the growth rate of publications for each group of cities,

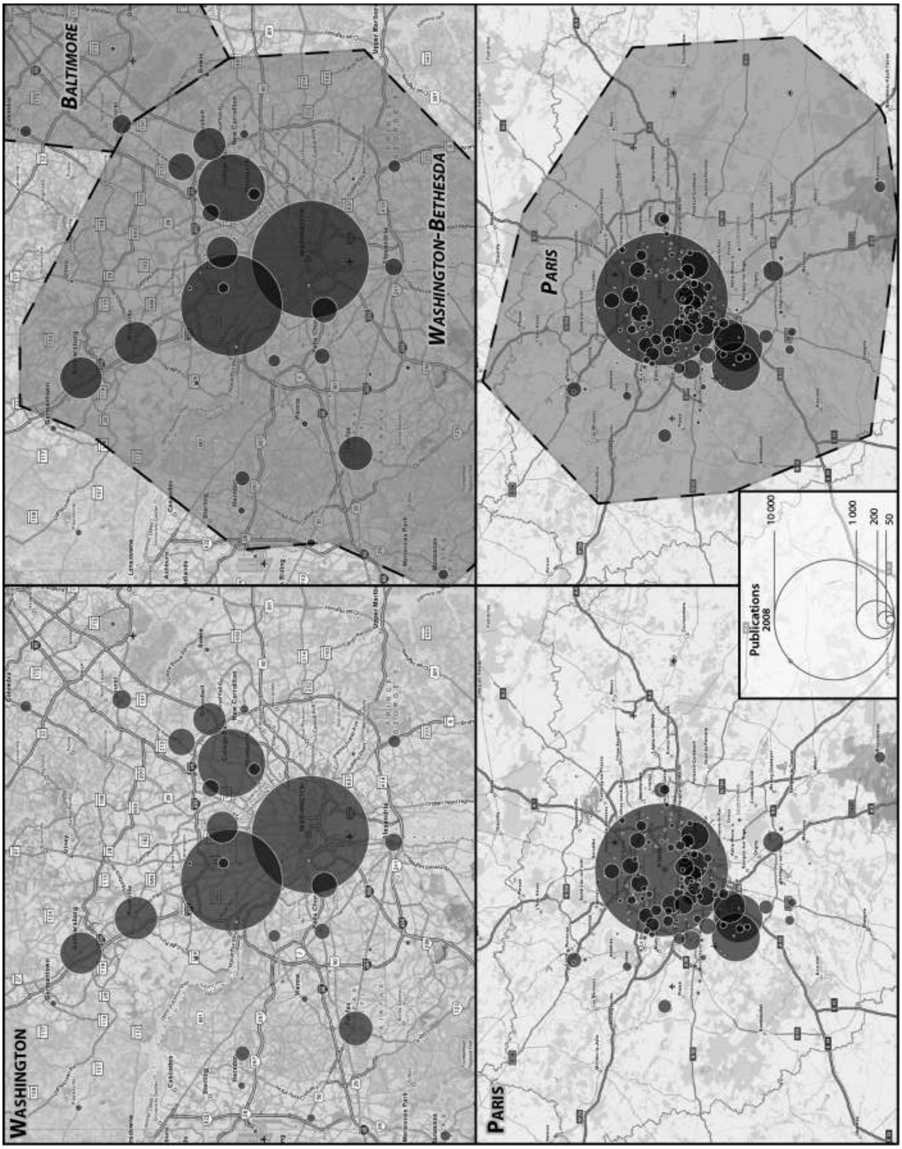

Figure 1. Regrouping localities by agglomerations: Washington and Paris. Left: isolated localities; right: aggregated scientific areas.

Table 1. Changes in the concentration of world publications in the most important cities.

Years agglomerations	Share of total publications 1986–1987–1988 (moving average) (%)	Share of total publications 1996–1997–1998 (moving average) (%)	Share of total publications 2006–2007–2008 (moving average) (%)
First 10	21.0	16.8	13.5
First 20	28.7	24.5	21.4
First 30	34.1	30.0	26.7
First 50	42.3	39.0	35.1
First 100	56.3	52.5	49.0
First 200	72.5	69.6	65.7
First 300	79.5	78.3	75.1

as did Matthiessen et al. (2010), and obtained a result that does not concur with theirs. Our findings state that the 30 major cities increased their publications by 28% between 1997 and 2007, compared with a global increase of 40%. The difference is due to the method of calculation; fractioning papers avoids the overestimation of bigger entities, produced by attributing collaborative papers to each collaborating unit.

To assess the extent to which city and country evolutions are linked, we carried out an ANOVA on the agglomerations of the 14 most productive scientific countries, which accounted for 72.7% of the total number of world publications in 2007.[2] Results showed that the rate of increase in the number of publications per country between 1997 and 2007 explains 72% of differences in publication rates between cities.[3] It is therefore necessary to proceed in stages and to examine the changing balance between countries before analysing their cities.

At the country level, scientific activity is deconcentrating

Reports published by Thomson Reuters[4] on the evolution of publications in different countries show a redistribution between the different areas of the world, with many 'emerging' countries contributing to the increase in global scientific output. The report on the USA notes that: 'The US is no longer the Colossus of Science, dominating the research landscape in its production of scientific papers, that it was 30 years ago. It now shares this realm, on an increasingly equal basis, with the EU27 and Asia-Pacific' (Adams and Pendlebury, 2010). They observe a similar trend, albeit at a later date and to a lesser degree, for citations received by publications, which provides a measure of the academic visibility of research. Huang et al. (2012) confirm these results, by analysing the number of papers, citations and patents.

Table 2 shows our calculations of the number of publications for the top 30 publishing countries in 2007 (time period 1987–2007); these calculations fully converged with the findings cited above.

Deconcentration is clear at the country level. In 1987, three countries alone (USA, UK and Germany) produced 50% of publications. Nine countries made up 75% of publications and with 20, the total reached 90%. In 1997, four countries (USA, Japan, Germany and the UK) accounted for 50% of publications. Eleven produced 75% of the world's production and 23 countries made up 90%. In 2007, the numbers are five countries (USA, China, Japan, Germany and the UK) for 50%, 14 for 75% and 26 for 90%.

Furthermore, developments indicated by this table can be summarised into two broad

Table 2. Evolution between 1987 and 2007 of the 30 most productive countries in world publications.

Country	Country/world share in 1987[a]	Country/world share in 1997[a]	Country/world share in 2007[a]	1987 rank	1997 rank	2007 rank
USA	34.3	29.8	24.5	1	1	1
China	0.9	2.4	8.6	18	12	2
Japan	7.3	9.0	7.8	4	2	3
Germany	7.4	7.4	5.9	3	3	4
UK	7.8	7.4	5.4	2	4	5
France	5.3.	5.5	4.3	5	5	6
Italy	2.5	3.4	3.5	9	8	7
Canada	4.3	3.7	3.4	7	6	8
India	2.6	2.2	3.0	8	11	9
Spain	1.3	2.3	2.7	13	9	10
South Korea	0.1	1.1	2.7	42	16	11
Russia	5.1	3.5	2.2	6	7	12
Australia	2.1	2.2	2.1	10	10	13
Brazil	0.5	0.9	2.1	27	21	14
The Netherlands	1.8	2.0	1.7	11	13	15
Turkey	0.1	0.5	1.6	44	26	16
Taiwan	0.3	1.0	1.6	33	18	17
Poland	1.0	0.9	1.4	17	20	18
Sweden	1.6	1.6	1.2	12	14	19
Switzerland	1.2	1.3	1.2	14	15	20
Belgium	0.9	1.0	0.9	19	17	21
Iran	0.0	0.1	0.8	73	51	22
Israel	1.0	0.9	0.8	16	19	23
Greece	0.3	0.5	0.7	31	28	24
Austria	0.6	0.7	0.6	23	24	25
Denmark	0.8	0.8	0.6	20	22	26
Finland	0.6	0.7	0.6	21	23	27
Mexico	0.2	0.4	0.6	35	32	28
Czech Republic	0.5	0.4	0.5	24	29	29
Singapore	0.1	0.3	0.5	45	35	30

[a]Fractional counting of publications, with 3-year moving average.

trends. The first is the increase and diversification of scientific activity at the world level. All indicators of this activity – the number of academic researchers, the number of universities, the number of students, etc. – converge to highlight the increasing endowment of most countries with universities and laboratories, with differences due, of course, to economic development. Roughly, the number of publications tends to be a linear function of GDP; therefore, economic growth has a direct consequence on research activity. There has been a noticeable development of science in emerging countries, particularly in Asia, as well as in Southern Europe (Greece, Spain, Portugal). Inversely, the relative regression of traditionally dominant zones (USA, Northern and Western Europe) can be attributed to slower economic dynamics, and former Soviet republics that have not joined the EU display a clear regression (Russia, Ukraine, Belarus).

The second trend is an increasing convergence between the data base and the reality of research practices. This is the result of two

Table 3. Changes in the share of publications of the world's major agglomerations in terms of their respective national production between 1987 and 2007.

Agglomeration	City/country share 1987	City/country share 1997	City/country share 2007	Changes in city/country shares 2007–1997
Tokyo	34.1	32.5	32.5	0.0
Beijing	34.4	26.5	21.1	−5.4
Paris	45.2	39.0	35.7	−3.3
New York	7.2	6.5	6.0	−0.5
Seoul	82.6	48.5	54.2	5.7
Boston	5.2	5.5	5.7	0.2
Kyoto	21.7	20.7	19.8	−0.9
London	27.1	23.5	22.2	−1.3
Berkeley	5.4	5.0	4.6	−0.5
Los Angeles	4.7	4.2	4.4	0.2
Washington	5.5	5.0	4.4	−0.6
Shanghai	18.4	11.1	10.8	−0.2
Moscow	57.6	47.5	42.8	−4.8
Taipei	51.4	51.1	44.5	−6.5
Toronto	19.6	19.5	20.6	1.1
Chicago	3.0	2.9	2.8	−0.1
Madrid	31.1	26.8	23.7	−3.2
Philadelphia	2.9	2.9	2.6	−0.3
Berlin	10.0	9.9	10.2	0.3
Durham Research Triangle	2.0	2.1	2.3	0.2
Sydney	24.1	26.0	25.4	−0.6
Rome	15.0	15.7	15.2	0.5
Cologne	10.1	9.8	9.0	−0.8
Singapore	100.0	100.0	100.0	0.0
Baltimore	1.7	1.9	2.1	0.2
Barcelona	19.8	19.4	18.8	−0.6
Munich	9.7	9.1	8.8	−0.3
Melbourne	24.6	22.8	23.9	1.1
Montreal	13.8	16.3	15.1	−1.2
San Diego	1.6	2.0	2.0	0.0

phenomena: first, the diversification of journals included in the data base,[5] and second, the increasing tendency of researchers to focus on journals indexed in this data base. The specific effect of this trend is the gradual reduction of the overestimation of the USA's importance (and to a lesser extent, that of the UK), whose journals were initially overrepresented. Part of the regression of the weight of the USA might be the result of a better representation of non-US publications in the data base.

Deconcentration within countries

There is a clear shift in the balance of scientific publications between countries, but this could very well be accompanied by increased concentration in certain major scientific cities, as suggested by Matthiessen et al. (2010). To test this hypothesis, we examined how the proportion of publications of large scientific cities has changed when compared with the total publications of their respective countries (Table 3).

Of the 31 most important cities in 2007, Singapore must be excluded because deconcentration is not possible in this city-state. Of the remaining 30, 20 saw their share decline, two were stable, and eight increased their ranking. Of the latter group, Seoul stands apart: after a significant, relative decrease between 1987 and 1997 (proactive policy in favour of Taejon), it regained a few percentage points in the second period. Melbourne is in a somewhat similar situation with a much smaller amplitude. Three US cities increased their figures, balancing out New York city's lower scores; but here, too, changes were slight. Toronto's increase is inversely proportional to Montreal's decrease, but this can be explained by the differential growth of the population of Ontario and Quebec and, as we shall see later, by the relative decline of Ottawa. Berlin is a unique case of a city that became a national capital during the 1990s, incorporating the dynamics of Eastern Germany.

Among those whose importance within their country diminished, Beijing, Paris, Moscow, Madrid and Taipei are the most visible. Beijing, Taipei and Madrid are in countries with increasing global rankings, but the number of their publications has increased less rapidly than that of other cities in the same country. Not only are Paris and Moscow in regressing countries (at least during the second period for France), but these cities are also undergoing a redistribution of shares in favour of other cities in their respective countries. The range of differences in the different countries is also highly variable. Though China, France, Spain, Russia, UK (or even South Korea over 20 years) are engaged in ongoing processes of deconcentration and the emergence of 'secondary' cities, other countries (USA, Canada, Japan) have limited variations and their 'scientific map' remains relatively stable. Italy and Germany require more detailed analysis. Their capitals were not initially in particularly strong dominant situations and the trends we observed are the result of the combination of separate processes.

The dimensions of deconcentration

The combination of changes in the overall balance between countries and in the relative ranks of cities within each country produces a variety of situations. Figure 2 shows the intersection of these two variables for the 30 highest ranking cities in terms of publications for the period 1997–2007.

To the right of the vertical axis are the cities within countries of growing importance, accompanied by an internal deconcentration (China, Spain) or coupled with a concentration in certain cities. However, this second scenario concerns only Seoul, whose particularity has been noted earlier. The same figure for the preceding period would have placed Seoul next to Beijing. Melbourne and Toronto show a relative, if slight, growth. Cities located to the left of the vertical axis are located in countries whose share of world publications is diminishing. Moscow, Paris and London are clearly in a process of deconcentration.

If we broaden our perspective (and consider the period 1987–2007), we can take as a deconcentration index the changes in the national shares of publications produced by the largest agglomeration of each country at the start of the period. Countries considered stable display changes in absolute value of less than 2% for a period of 20 years. The 70 countries considered in Table 4 produced 90.1% of world publications between 1997 and 2007.

Table 4 clearly shows that the vast majority of countries underwent a process of internal deconcentration at various periods. The group of stable countries includes many countries that have not deeply transformed their university system (North America, Japan, certain European countries). The rare

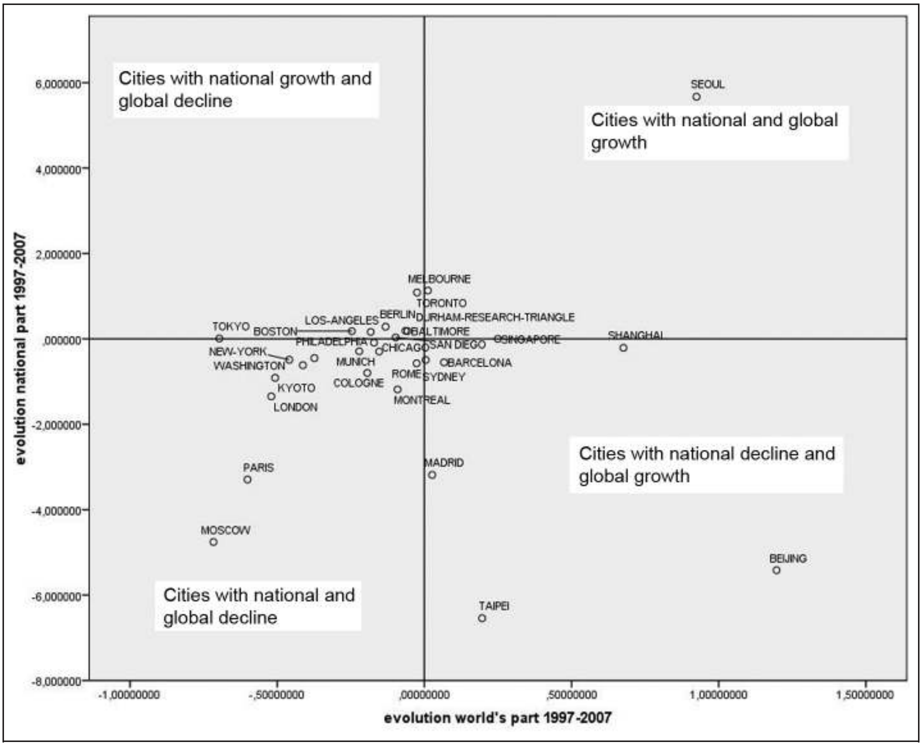

Figure 2. Evolution of the global and national share of the 30 highest ranking cities (1997–2007).

Table 4. 1987–2007: Deconcentration and concentration trends of the 70 countries that produced the most scientific publications between 1997 and 2007.

1. Deconcentration	
Algeria, Argentina, Austria, Bangladesh, Belarus, Belgium, Brazil, Bulgaria, Chile, China, Cuba, Czech Republic, Denmark, Egypt, Estonia, France, Greece, Hungary, Ireland, Israel, Kenya, Lebanon, Lithuania, Malaysia, Mexico, Morocco, Nigeria, Norway, Philippines, Poland, Portugal, Romania, Russia, Saudi Arabia, Slovakia, Slovenia, Spain, Taiwan, Thailand, Tunisia, Turkey, UK	
2. Stable	
Australia, Canada, Croatia, Finland, Germany, India, Iran, Italy, Japan, The Netherlands, Pakistan, Serbia, Singapore,[a] Sweden, USA, Uruguay, Venezuela, Vietnam	
3. Concentration	
Armenia, Colombia, Jordan, Kuwait, New Zealand, South Africa, South Korea, Switzerland, Ukraine, United Arab Emirates	

[a]Deconcentration is impossible in the city-state of Singapore.

cases of concentration (only six out of 70 for the period) all correspond to particular histories with specific policies: the specific development of Polytechnic Institutes in Switzerland; imbalance between Auckland and Christchurch in New Zealand; the closing of research centres in Cali which automatically raised Bogota in the ranks of Columbia's total publications, etc. It should be noted and even emphasised that there is no correlation between a country's publication growth rate and its tendency towards concentration or deconcentration.

In order to characterise the basic processes at work in the spatialisation of scientific research, we have focused on the evolution of the main scientific city in comparison with the rest of the country. The reasons behind the changing geography of activities within a country are complex and require more in-depth studies, including the analysis of specific policies. Such detailed analysis is beyond the focus and scope of this paper. We can, however, examine more closely certain representative countries. First, there is China, a fast-growing country. Then three European countries: Spain, a country to the south of the continent that is catching up with its northern neighbours; Germany, a former heavyweight in terms of scientific research that has undergone territorial redefinitions; and France, another important scientific power whose territorial balance is changing as higher education grows. Finally, there is Canada for northern America with a highly stable scientific geography.

In 1988, China was a minor contributor to international science (that is to say within the perimeter of the 'international' journals indexed in the SCI-Expanded), producing a little over 1% of SCI-Expanded publications, mainly in Beijing and Shanghai where over half the Chinese production was concentrated (52.2% in 1986–1988). The astoundingly rapid development of science in this country (almost 10% of all publications in the late 2000s are Chinese) was accompanied by a very significant deconcentration process within the country: Beijing and Shanghai account for only a small third (31.9% for 2006–2008) of the national scientific production; Hong Kong, which had joined the system of international science early on, saw its share decline. Today, many large cities within the country are well ranked (Nanjing, Wuhan, Hangzhou, Xian, Guangzhou), each producing more than 3500 publications per year. Nanjing and Wuhan are currently in the top 40 scientific cities worldwide. Even outside of these very large urban centres, the rest of the country has significantly increased its share: the entire urban system is progressing faster than Shanghai and Beijing.

Spain is one of the European countries that dramatically increased its scientific activity during the 1980s and 1990s. As a result, the country has moved up in the world ranking: in the late 1980s, it ranked 13th largest producer of science worldwide, today it is placed 10th (with 2.7% of SCI-Expanded publications). The Spanish scientific system is undergoing a notable deconcentration. At the beginning of the period, it was dominated by two major urban and university centres: Madrid (31%) and Barcelona (19.7%), which together produced over half of all Spanish publications. Since, Spain has been moving towards a more polycentric organisation. In 2006–2008, Madrid and Barcelona represented only 42.5% of the total production. In fact, Barcelona decreased slightly (−0.9 percentage points) while Madrid fell sharply (with −7.3 percentage points in 20 years). Is this related to Spain's strong decentralisation process that began after 1975? In the other major scientific centres, situations were mixed: only the third largest city, Valencia, clearly saw its scientific production progress within total Spanish production (6.4 to 7.5%), while other cities either stagnated (very slight growth for Zaragoza) or regressed (Sevilla, Granada, Oviedo, Santiago, Murcia, Santander). It is the smaller scientific centres that have most benefited from the growth of scientific activity in Spain. In the European context, Spain is an exemplary case of extensive deconcentration in the context of strong GDP growth.

For decades, Germany has been a leading scientific country: in 1986–1988, it ranked third worldwide, after the USA and the UK (with combined GDR and FRG publications). Today, it ranks fourth behind the USA, China and Japan. It accounts for 5.9% of the publications listed in the SCI-Expanded. Germany's reunification, a major geopolitical event, is of course a key factor in understanding the country's evolution. Berlin, the country's current leading scientific centre, despite all the scientific restructuring in the eastern half of the country, has certainly benefited from its reclaimed position as the nation's capital, from the reunification of Berlin's academic space (which now includes former East and West Berlin, as well as the city of Potsdam), and from the care given to restoring its influence. This is the only major German city to have increased its share of scientific production. Right behind Berlin, Cologne and Munich ranked lower in 2006–2008 than 20 years earlier. This is generally the case for western Germany's large scientific centres, which have all slipped slightly, but in varying proportions. Overall, the most visible phenomenon is the growth of scientific centres in Eastern Germany (Dresden, Leipzig, Jena, Halle, Rostock), which probably corresponds to a period of catching up after reunification. Dresden is particularly remarkable for the strength of its growth, having become the seventh most important scientific centre in Germany.

France, another long-standing stronghold of science has evolved along the same path as Germany, losing a notch (sixth in 2006–2008) owing to the rise of China. The most striking aspect of France is the decrease in Paris's importance, which lost nearly 10 points (from 45.1 to 35.7) in 20 years. The decline of Paris' relative importance is due to the massive expansion of the higher education system in the rest of the country. This drop has benefitted both the major, long-standing scientific centres outside of Paris (especially Toulouse, Grenoble and Rennes), as well as small university centres that have recently developed. Two traditional scientific cities have not benefited from this global redistribution: Nancy's share of national publications has stagnated and Strasbourg has declined (−0.9 points). Both are cities to the east of France, a region whose economic development has been weaker than more southern regions.

Canada currently accounts for 3.4% of world scientific output (eighth place in 2006–2008). Toronto, Montreal and Ottawa were the foremost centres 20 years ago, but the top three are now, in order, Toronto, Vancouver and Montreal, demonstrating the overall vitality of British Columbia. Of all the country's major cities, only Ottawa has declined significantly and continuously from 1986–1998 to 2006–2008, largely because of budget cuts in federal government laboratories, strongly represented in the Ottawa region. For the others, changes are quite different between the first and second decade. Montreal, which rose over 20 years (+ 1.4 points), saw its share decline over the past 10 years; while Toronto's recent activity has been much stronger, corresponding to differences in growth rates between the two cities. Otherwise, changes are rather slow because of very gradual changes in the country's scientific systems.

Conclusion

Contrary to the prevalent belief in many debates and decisions on scientific policy, the overall trend is not towards a concentration of scientific activities in 'global cities'. Rather, we are observing what is primarily a loss of hegemony of the usual central countries (USA, UK, Germany, France), accompanied by particularly strong growth in Asian countries (China, South Korea, Taiwan), and more broadly many 'emerging' countries. This development contributes to diversifying production sites of scientific papers. Furthermore, we have observed within many countries (Russia, France, Spain, UK, China, etc.), regardless of the overall development of the national scientific production, a trend towards deconcentration with increased production in 'secondary' cities. The first countries to undergo deconcentration processes (USA, Canada, Germany, for example) have a rather stable scientific geography. Countries currently concentrating their scientific production are rare and explanations can be found for each in the changes in their demography, economy and scientific organisation.

How can the deconcentration trend be explained? In fact, our observations of deconcentration processes align with the hypothesis that, at the aggregate level of all disciplines in an urban area, the number of publications is, roughly, a linear function of the number of academic researchers working in that same area. The problem is then to account for changes in the number of 'scientific producers' in urban areas. In most countries, these developments are closely related to those of higher education. In many countries, and with a few exceptions, such as universities with very high ratios of teachers/students (e.g. Caltech), the number of academic researchers is approximately a linear function of the number of students. All countries with a geographical deconcentration of publications have also experienced, at one time or another during the last 30 years, an increase in the number of students attending institutions of higher education. Furthermore, this increase has not been concentrated in existing central urban areas and their institutions; but rather, has been observed in more peripheral urban areas with more recent higher education institutions. In contrast, countries in which there is no evidence of deconcentration have not witnessed a significant change in their student population in the recent past. As the geographical distribution of higher education evolves, so too does the spatial diffusion of scientific activity as measured by publications.

This paper has focused only on the production of publications. This approach measures standard scientific activities and does not aim at identifying only the 'best' papers or the 'breakthrough' in given fields of research. The analysis of the scientific impact of these papers is a different question that could be studied through citation analysis. But before analysing the concentration (or not) of citations, it had to be shown that, contrary to what is often said, the production of papers among countries and among cities in a given country is generally deconcentrating, *not* concentrating.

So, the next step would be to analyse the impact of these publications by examining how they are cited. Here we can only indicate some ideas on the basis of partial research already done. Recent studies already show that highly cited researchers are not particularly concentrated in cities with high citations figures (Bornmann and Leydesdorff, 2011). Moreover, a study of French citation rates (Grossetti and Milard, 2011) shows that even though citation rates of Paris publications remain ever so slightly higher than those received by publications written by scholars in other cities, the difference between the two is decreasing. Finally, it has been shown that among all publications, there is a clear deconcentration of citations over time at the world level (Larivière et al., 2009, 2013; Lozano et al., 2012). The same deconcentration has also been shown for China using the Chinese Citation Index (Yang et al., 2010). Even if this does not exclude that there may be different patterns in some research domains, it is likely that the citations follow the same trend as the publications when considering all disciplines.

It would also be necessary to conduct an analysis of co-authoring networks. Is the emergence of new scientific centres at the expense of larger centres, or do they benefit from the diversification of production sites by increasing their centrality? The comparison of large networks over time, in a context which is itself evolving, poses difficult methodological problems and would require additional research.

In summary, our results demonstrate that standard scientific activities are more widespread geographically over time as well as more visible than ever, and that there is no real trend towards concentrating activities in so-called 'world cities'. This result does not invalidate the concept of 'global city'. It simply points to the fact that the so-called global cities concentrate less standard scientific activity than they did in the past. As the planet's overall economic and social structures are changing, scientific activities are spreading across a wider geographic area. Our data and analysis show that the system of cities of scientific research is evolving, leading to newer, more numerous, and increasingly dynamic nodes of scientific production throughout the globe.

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Notes

1. Basemap: © OpenStreetMap contributors.
2. USA, China, South Korea, Japan, France, Canada, Germany, UK, Brazil, India, Spain, Italy, Russia, Australia.
3. $R^2 = 0.728$ (adjusted $R^2 = 0.715$).
4. See the series of *Global Research Reports*, published online by Thomson Reuters in 2010.
5. The number of journals included in the WoS has grown from 3604 in 1978 to 4250 ten years later, to 5447 in 1998 and to 7470 in 2008.

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