Science Productivity, Higher Education Development and the Knowledge Society (SPHERE Project)

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List of Acronyms

SCIE	Science Citation Index Expanded Data
SPHERE	Science Productivity Higher Education and Research Economy Project
STEM+	Science, Technology, Engineering, Mathematics and associated fields
TR	Thomson Reuters
WoS	Web of Science

Executive Summary

This project created and analyzed a new, large global data set on scientific journal articles between 1900 and 2011 and a series of case studies to examine how systems of higher education developed and grew nations' capacity for scientific research. The analysis resulted in a series of new insights about global scientific production that were only possible with a consideration of long-term trends. First, despite predictions as early as the 1960s that the growth rate of "big science" would slow, the dataset shows in fact that "big science" started a phase of exponential growth in the early 1960s that has continued unabated for decades. "Big science" has transformed into "mega-global science," and the trends of global diffusion and regional differentiation began much earlier in the 20th century than is commonly understood. Second, the analysis of rates of regional journal article production also depicts clear shifts in the competition for ascendancy in scientific production. For the first half of the 20th century, global competition for scientific impact was primarily an Atlantic battle between the top producers of Europe (Germany, France, and the U.K.) and the United States. The locus of competition shifted by the end of the 20th century to a contest between the current research "superpower," the United States, and the fast-growing producer, China, along with the many less populous countries of Western Europe with their highly productive science systems. With the contributions of other East Asian high volume producers such as Japan and South Korea in the later decades of the 20th century, and simultaneous slowing of research production in U.S. science, the center of gravity for research production has been pulled eastward for the past two decades. Third, while science may indeed be an inherently global and collaborative enterprise, the trend toward global collaboration of authors is a relatively recent one. Historically, one-third of all research articles worldwide result from international collaboration, and less than 26 percent are the product of one researcher

alone. In 1980, however, only about 2 percent of all SCIE publications involved a collaboration across international lines. Three decades later, this proportion is eleven times what it was in 1980. Finally, the study also concluded that overall volume of production is not a sufficient measure of scientific capacity by itself. When adjusting for the size of population and the economy, the proportion of GDP spent on R&D, or the number of researchers, some smaller countries (especially in Europe) are more productive on a per capita basis than mid-sized or even larger ones. Similarly, the ratio of investment in science to scientific production is much higher in the high volume producers than it is in some small states. While output is smaller in these states, they have maximized R&D investments more efficiently than their larger competitors.

1. Introduction

This project created and analyzed a new global data set on scientific publications and a series of case studies to examine how systems of higher education developed and grew nations' capacity for scientific research. The project is best understood in the context of the global knowledge society, which was precipitated by three trends: the institutionalization of education (Meyer, 1977); massive expansion of university enrollments around the world (Meyer, Ramirez, Frank, & Schofer, 2008; Schofer & Meyer, 2005); and increased scientization in global culture (Drori, Meyer, Ramirez, & Schofer). As new universities were founded around the world, and tertiary education became increasingly accessible, the research university became a global paradigm for higher education and knowledge production. Educational expansion led to new forms of knowledge and policymakers looked to science education as a source of economic growth (Drori, 2000).

1.1 Background of Project

This project was the first of its kind to analyze factors behind cross-national trajectories of scientific knowledge across the last century. Systematic historical quantitative cross-national comparisons were used to examine national differences in contributions to global science. Most importantly, the cross-national database provides indicators to assess the influence of higher education development and science capacity-building on science production. In addition to its scientific value, the results will inform national and international policymakers seeking to enhance national contributions to the global enterprise of science. Our findings can support policy recommendations to meet the challenges of the global knowledge society.

1.2 Objectives of this Study

The main objective of the project was to assemble a multi-national expert scientific team to assess the impact of the research university and expanding higher education on postindustrial society.

1.3 Project Tasks/Aims

- Conducted qualitative-historical case studies of national models of higher education development and science capacity-building (China, Germany, Japan, South Korea, Qatar, Taiwan, United States)
- Created and analyzed a cross-national dataset of science productivity using data from Thomas Reuters (Web of Science) of all research published between 1900 and 2011
- Disseminated research findings by presenting at international conferences (e.g., Qatar Foundational Annual Research Conference, 2013, and the annual meeting of the

Comparative and International Education Society, 2015) and publishing in high-profile outlets (e.g., *Change: The Magazine of Higher Learning*)

2. Literature Review

University-affiliated research complements science production in the private and governmental sectors in several ways. Government research was often developed for military purposes, but the military gradually declined as an institution while universities took on more central roles in society (Etzkowitz & Leydesdorff, 2000). University researchers have tended to be more focused on long-term knowledge production that led to the rise of new, interdisciplinary fields such as molecular biology and biotechnology (Etzkowitz, Webster, Gebhardt, & Terrra, 2000). Similarly, Hall, Link, and Scott (2003) found that because universities tended to be involved in knowledge production in emerging areas of scientific inquiry, those research projects were often problematic. Although those projects "experience[d] more difficulty and delay" the involvement of university partners meant that the studies were less likely "to be aborted prematurely" (Hall, Link, & Scott, 2003, p. 485). In part, these types of findings have been attributed to academic freedom as a central tenet of the research university and faculty members' prerogative to pursue research on new topics without corporate constraints (Aghion, Dewatripont, & Stein, 2008).

Although research universities were historically sites of knowledge production (Schofer, 2004), many scholars began to predict that the locus of scientific research would shift away from higher education. In *The New Production of Knowledge*, Gibbons and colleagues predicted that "universities, in particular, will comprise only a part, perhaps only a small part, of the knowledge producing sector'' (Gibbons, et al., 1994, p. 85; see also Godin & Gingras, 2000). The *New*

Production of Knowledge began a lively debate about the state of scientific research and the role of the research university in contemporary society—in fact, it was the most widely cited work on the topic (Hessels & van Lente, 2008).

Scholars from various fields introduced competing models of the university's role in science production such as "finalization science," "academic capitalism," and "post-academic science" (Hessels & van Lente, 2008) and the "emerging global model" (Mohrman, Ma, & Baker, 2008; Baker, 2014). These models all acknowledged that universities have changed the ways in which they produce science in an increasingly collaborative, globalized, and resource-constrained world. However, some of the models have lacked empirical bases and have led to different normative judgments and implications for policymakers. As stated above, because university-affiliated researchers have some measure of academic freedom and are less-constrained by profit motives they can help produce knowledge in nascent areas of scientific inquiry and buoy troubled projects. If policymakers think that universities are contributing to declining shares of science production, they will not only have fundamental misunderstandings of how knowledge is produced, they may misallocate resources that support scientific research.

The Limits of Empirical Studies on Science Production

Studies of knowledge production have often been limited in that they have not considered how different institutional models have shaped science capacity across countries. For example, Gantman (2012) used data on scientific findings that were published in 2009 to show that across countries, differences in knowledge production in the hard sciences were related to economic factors and not differences in political regimes. However, Gantman did not consider universities in his models. Other comparative studies have considered the number of universities in each country, but have not focused on the different institutional models that shaped the development of the higher education sector, and ultimately, universities' capacity for scientific research (e.g., Meo, Al Masri, Usmani, Memon, & Zaidi, 2013; Meo, Usmani, Vohra, & Bukhari, 2013; Teodorescu, 2000).

Until now, our understanding of the long-term development of global science production has been limited by available data. Empirical studies and bibliometric analyses have examined scientific publications as early as the 1970s (Schofer, 2004), but most have focused on decades since 1980 (Adams, 2009; Adams, Black, Clemmons, & Stephan, 2005; Bornmann & Mutz, 2015; Godin & Gingras, 2000) or 1990 (Bornmann, Wagner, & Leydesdorff, 2015; Meo, Al Masri, Usmani, Memon, & Zaidi, 2013; Meo, Usmani, Vohra, & Bukhari, 2013). This has severely limited the ability to conduct rich, comparative case studies that examine how different institutional models evolved in historical context. This is necessary if we are to understand the factors that affect capacity-building by region and to make meaningful comparisons across countries.

A Brief History of Bibliometric Analysis

Bibliometric databases are used to collect information about publications of a single researcher, a research group, or an entire organization (Havemann, 2009). These databases are used as a tool to get insights into the scientific publication output in general, the integration of the scientific community, and international visible research results (Ball & Tunger, 2005). Nevertheless, bibliometrics as an independent field of research deals with the statistical analysis of bibliographic information, especially with the study of authors, publications and organizations. The French term *bibliométrie* was introduced by Paul Otlet in 1934, and gained worldwide fame much later in 1969 when Alain Pritchard defined the English term *bibliometrics.* He described bibliometrics as "the application of mathematical and statistical methods to books and other media of communication.” Other researchers define bibliometrics as a discipline much further as a quantitative study as they are reflected in the bibliographies (e.g. White & McCain, 1989), or as “the application of those quantitative methods which are dealing with the analysis of science viewed as an information process” (Glänzel, 2003, p. 6), or they put under bibliometric research all aspects and models of science communication, storage, distribution, and publication (Glänzel & Schöpflin, 1994).

Publishing and citing have been done for thousands of years, even if it is not about classical scientific references as we make sense of them today (Jovanovic, 2012). Outstanding bibliometric analysis were conducted by Alfred J. Lotka (1926), Samuel C. Bradford (1934), and George K. Zipf (1949). Further milestones followed in the history of bibliometrics in the 1960s and the 1970s: The first publication of the *Science Citation Index (SCI)* in 1963 (Garfield, 1964) and the publication of the work of Derek J. de Solla Price (1961 & 1963) popularized bibliometrics worldwide and helped to establish itself as an independent research area (Gläzel, 2003). The tremendous increase of computing power and the invention of citation indices made it much easier for researchers to analyze publications and citations automatically and in very large quantities. Due to the changing scientific landscape, bibliometric analyzes are applied as an evaluation instrument of scientific capacity (Ball & Tunger, 2005). They are a strong instrument of scientific management and science policy. Target groups of this particular form of quantitative analysis are bibliometricians (for basic research), scientific disciplines (with wide-ranging interests), and science policy and research management organizations (Glänzel & Schöpflin, 1994).

3. Methodology

The centerpiece of this project involved the creation of a new, large data set that included all scientific journal articles published in peer-reviewed journals within Thomson Reuter's SCIE collection of STEM+ journals between 1900 and 2011. The following section describes how this dataset was created.

Data Source and Coding

This analysis is based on Web of Science Publication Data (Science Citation Index Expanded; hereafter "SCIE") compiled by Thompson Reuters (TR) from 1900 to 2012 and obtained by the research team in the fall of 2012. Data included every five years from 1900 to 1980 and every year from 1980 to 2012. Since data for 2012 was not completed at the time of delivery from TR, 2011 was the final year that was analyzed. We focus here only on research articles (of varying length), not on other types of publication in the database. For SCIE data from 1900 to 1970, we found that the majority of research articles[1] were missing information on institutional affiliation and/or address and country information. The proportion of country information from 1900 to 1940 missing ranged from 56% to 90% annually. The proportion from 1945 to 1970 missing was even greater, from 98.6% to 99.8%; thus, analysis of global trends by country prior to 1975 would have been impossible for some years and highly unreliable for others. Given this situation, we randomly sampled and coded the journal articles for each of the relevant data years by directly consulting the scientific journals—in archives, libraries as well as Internet-based databases—in order to make reliable population estimates.

[1] Web of Science has its own categorization of writings in their database such as research article, review, editorial, letter, etc., which we also keep in our working process. In other words, an "article" or "research article" in this report means that it is classified by TR as a research article (k_code = @).

We proceeded as follows. First, we selected journals[2] through a stratified sampling procedure. We extracted a list of all the journals for each year from TR data and then we grouped those journals into four categories: S (Science), T (Technology), H (Health), and O (Others). Second, we randomly selected 5% of all the journal titles reflecting the composition rate of those four categories in each year. If 5% of journals amounted to less than 30 titles, we randomly selected more journals in order to make the number of our sampled journals equal 30 for all categories combined in that year. For example, there were 226 journals in 1940, and 35% of them were categorized into "S", 10% into "T", 55% into "H", and 0 into "O". This resulted in 11 journals in category "S", 3 in "T", and 16 in "H" for 1940. Following this procedure, 30 journals were randomly selected every five years from 1900 to 1960. Sixty-four journals were selected for 1965 and 108 for 1970. Journals in the "Other" category were included only for the years 1940, 1945, 1965, and 1970. In 1970, two out of five selected journals in this category were not coded because they were sociology journals (non-STEM).

In order to estimate the time it would take to code each article, we experimented with some selected journals from 1950 to 1960 (8 journals in 1950; 7 in 1955; 1 in 1960). Based on this sample, and with the advice of statisticians collaborating in the project, we randomly selected 30 articles from each annual journal volume when there were 35 or more articles in that journal, while all articles were coded if there were less than 35 articles. Coders sometimes found that selected articles did not qualify as research articles. (This reflected coding errors in the original SCIE data purchased from TR.) Similarly, in a small percentage of cases, coders could not find articles selected from SCIE data in the print or electronic versions of the journal. In both cases, replacement articles were selected to maintain a minimum of 30 articles for each journal. If all the listed articles were already coded, then the problematic article identification number

[2] A journal title was counted only once, no matter how many volumes or issues in each year were published.

("Accession Number" in the Web of Science system) was dropped and the total number of articles for that journal decreased accordingly.

We established three additional replacement rules for the journals. First, if the missing rate of country information for authors in one journal was greater than 20%, that journal was dropped and another journal was randomly selected. This rule was applied to coding from 1940 to 1970, and all journals with a missing rate greater than 20% were replaced. The only exceptions were for one journal in 1950 and two in 1970. Those three journals were kept in our coded data despite exceeding the 20% missing rate because any coded results were deemed preferable to journals with completely missing country information.

For the period 1900-1935, finding journals with 20% or fewer articles with missing country affiliation was difficult because journals were less likely to note authors' institutional affiliations in articles. This necessitated an additional coding procedure in order to locate author affiliations. For those journals with over 20% missing rate between 1900 and 1935, coders searched the Internet to identify the author's name and affiliation. If the author's name was not identifiable through Internet research, the Web of Science website was used to infer the author's country information based on his or her affiliation in other publications around the same time. This coding strategy was used only for country information, not for organization information. If neither searching the Web of Science online portal nor searching other databases was successful, that case was coded as missing.

There was another situation that required us to replace a few journals after the first round of random selection. The total number of articles based on our TR Data in some selected journals did not match the total number of articles of the same journals on the Web of Science website. For example, in the Journal 'Physical Review A' in 1970, there were 429 articles based on the search result on the Web of Science website, but the TR data contained only 293 articles. Such journals were not coded, but replaced with new randomly selected journals. Finally, a few selected journals did not include any research articles. They featured only reviews, editorial essays, and comments. These journals were also dropped and replaced by random selection.

It is a common critique of the Web of Science data that journals written in English are more likely to be included in its database than those in other languages. During the coding process, it was found that the replacement journals for the journals that were not published in English were likely to be journals that were published in English. Thus, if we dropped non-English language journals due to the 20% missing rule, non-English language journals were even less likely to be included in our sampling procedure. In order not to exaggerate this bias, two French journals (in 1940 and 1945) and three Russian ones (in 1970), even though they firstly violated the 20% missing rule, were included after Internet searches for author information. The data purchased from TR also included a small percentage of journals not traditionally considered to be in STEM fields. TR indicated that some journals are indexed in both the Science Citation Index Expanded and the Social Sciences Citation Index due to their cross-disciplinary nature. We did not exclude these cross-disciplinary journals for the analysis, especially for the years from 1980 to 2011, due to their inclusion in SCIE and their relevance to STEM researchers.

How We Counted Research Articles

International collaborations give rise to technical problems in counting publications. When counting total publications worldwide, we use the number of unique research articles regardless of the affiliated address of each article. That is, any collaborative paper is counted as one, regardless of the number of authors and countries involved. In other words, we do not double (or multiple) count collaborative publications.

When counting publications in each country (or each region), things become more complicated. Consider a publication with the following coauthors: 2 from the United States, 1 from Germany, and 1 from France. There are three options available in the bibliometric literature. The first option is whole counting, in which one credit is conferred to each country contributing to a publication. For the above article, each of the three countries (i.e., the United States, Germany, and France) gets 1 credit. One problem of whole counting is that the numbers are not additive, i.e., the sum of country numbers exceeds world total due to international collaboration. This is especially important when counting publications by regions. That is, if one is interested in comparing regional production (e.g., the US, EU, and East Asia), then the above publication should be counted as 1 for the United States, and 1 for EU. The second option is called whole-normalized counting in the literature, in which 1 credit is divided equally among the countries contributing to a publication. For the above publication, each of the three countries (i.e., the United States, Germany, and France) gets 1/3 credit. The last option, called complete-normalized counting, further takes the number of authors into account. For the above publication, the United States get ½, Germany gets ¼, and France gets ¼. Since TR data only contain research addresses, the third option cannot be applied because we do not know the exact number of authors associated with each research address; however, it is possible to assign the credit based on research addresses.

Weights for Population Estimates (only for Coded Data from 1900 to 1970)

The weights to project the population of publications from 1900 to 1970 were calculated considering the fact that the journals and the articles did not have the same probability of being drawn. The number of journals in each category differed as did the number of articles in each journal. Thus, the first weight (w1) reflects the reverse probability of journals to be selected considering the number of articles in all the journals: total number of articles in all the journals in each category divided by total number of articles in the only journals that are actually coded in each category. Secondly, the reverse probability of articles to be selected (w2) is calculated as the total number of articles in each selected journal divided by the total number of articles actually coded in the same journal. Multiplying the first and second weights becomes the weight for our analysis. The whole count of our weighted coded data is very similar to that of the original TR data. The ratio between the two ranges from .94 to 1.03. Otherwise, the team adopted the whole count method, which is widely accepted in bibliometric studies

The Dissolution or Unification of Countries

Because of the significance of an author's country affiliation for our analyses, the dissolution or unification of countries (for example the former Soviet Union, Yugoslavia, and Germany) required careful attention. Because of the lag time between article submission and publication date, a decision rule was adopted that allowed an article to be attributed to the former state/country up to three years after the date of political regime change. For example, USSR was divided into 15 nations on December 26, 1991. Based on the 3-year rule, USSR in TR data was coded as such until 1994. If an article attributed to an author from a research organization in the USSR appeared in 1995, the country affiliation was recoded into the correct current country name by cross-checking the city or organization as necessary. Similarly, if countries such as Russia, Azerbaijan, and other states of the former Soviet Union were identified in the TR data before 1991, they were recoded as USSR. During the period prior to 1949, when occupied Germany was divided into the Federal Republic of Germany (West Germany) and the German Democratic Republic (East Germany), all articles published by scientists in research organizations in the territories belonging to Germany were counted as German. After reunification in 1990, articles from authors in both parts of the country were again attributed to Germany. Precise coding rules are available upon request.

Comparison of Web of Science (Thomson Reuters) and Scopus (Elsevier)

The two main databases for international scientific journals publication, Elsevier's Scopus and the Web of Science (WoS) Thomson Reuters (TR), were compared to discover differences in coverage. The results show that the two databases exhibit similar trends in overall production. We chose ten countries (DEU, USA, JPN, CHN, TWN, KOR, GBR, FRA, RUS, and QAT) to compare whole counts from each database. The recoded TR data from 1900 to 1970 in the SPHERE database consist of the randomly selected, coded, and weighted data; thereafter, we use the regular WoS database. The correlation coefficient for each country between the Web of Science and Scopus data follows: DEU: 0.956; USA: 0.959; JPN: 0.979; CHN: 0.993; TWN: 0.998; KOR: 0.998; QAT: 0.983; GBR: 0.970; FRA: 0.958; RUS/USSR: 0.545. In most countries, the publication volume in Scopus surpassed that recorded in WoS between 1995 and 1996 and we find more publications in Scopus than WoS for each country through 2011. Similar increasing or decreasing trends for each country were found using both datasets. The slope indicating increasing or decreasing trends from each dataset roughly matched, except in the case of Russia (USSR), which showed noticeable differences in the representation of journals in the two databases.

4. Discussion of Results

Higher education and research are key pillars of the knowledge society. This report presents first results of a multi-year, cross-national investigation of the influence of higher education development and science capacity-building on scientific knowledge production

(SPHERE). Although there have been important descriptive reports of recent cross-national differences in scientific productivity, this study uniquely includes systematic analysis across an extensive historical scope (1900–2011). The project shows how differences in national models in developing research universities and institutes explain long-term cross-national trajectories in scientific productivity. Comparing dynamics in the world's oldest and largest research environments with trends in fast-developing knowledge economies, the SPHERE project analyzes differences in scientific productivity and institutionalization pathways in selected countries in Europe, the US, the Middle East, and East Asia.

The country cases studied in-depth thus far include Belgium, China, France, Germany, Japan, Luxembourg, Qatar, South Korea, Taiwan, and the United States. We also emphasized the mapping of global growth, regional competition, and collaboration across borders that have led to the surge in scientific productivity worldwide. The evolution of Science Citation Index publications from 1900 to 2011 shows major shifts in the regional development of science—and the recent growth especially in China and East Asian countries. Regarding the United States, the largest science producer for decades, we find that its world-leading capacity is built upon American mass higher education, especially since the Second World War. In Europe, our comparisons of higher education and extra-university research institutes show that these different organizational forms have contrasting contributions in Germany and France—traditionally top science producers—in comparison to neighboring smaller countries Belgium and Luxembourg. Despite the different relative significance of these organizational forms in each of these Western European countries, both are crucial to overall scientific productivity.

Further, science productivity in Japan has been shown to depend not only on the elite universities, but also on the range of national universities throughout the country. Our research on South Korea shows the significant contribution of private universities and investments to the fast growth of that country's higher education and research system. Qatar, one of the most rapidly-growing countries anywhere in the world has, within fifteen years, developed a comprehensive national research system. All of these country cases examined thus far show how higher education and research, as key pillars of the knowledge society, have developed since 1900. (See the "Case Studies" section below for a more complete summary of findings for these and other countries.)

Mega-Global Science

Long historical trends in scientific discovery led mid-20th century scientometricians to mark the advent of "big science"—extensive science production (de Solla Price 1961, 1963). They also predicted that over the next few decades, the exponential growth would slow, resulting in lower rates of increase in production at the upper limit of a logistic curve. They were wrong. The findings of the SPHERE project—new systematic estimates of the number of worldwide science publications from 1900-2011—show that, in fact, "big science" was itself transformed by unprecedented production beginning just after mid-century. Despite major wars and global economic crises, there has been no decline or slowing of exponential growth up to today. This remarkable growth reflects two contrasting and simultaneous trends—rising competition across nations and international collaboration among scientists.

Mega-global science has been powered by strong European science systems that pioneered discoveries over the centuries and were rebuilt in the 1950s after the Second World War. Another pillar is North American investment in science capacity rising over the twentieth century. The third dominant region with expanded science capacity is East Asia, especially Japan (since the 1970s), China, Taiwan, and South Korea (all since the 1980s). Most recently, strong investments by countries in the Arabian Gulf countries have established infrastructure and provide global sites for research, especially in dozens of international branch campuses, although there overall contribution to global production of journal articles is small.

The SPHERE project members coded and analyzed over 20 million records from Science Citation Index Expanded (SCIE) dataset to show that the number of research papers published in scientific journals over the 20th century grew extraordinarily rapidly (see Zhang, Powell & Baker 2015). Starting from slightly below 10,000 in 1900, the annual number of new SCIE publications grew to about 50,000 in 1955. This early trend, often referred to as "big science," was then transformed into what we call "mega-global science": an exponential annual growth rate of 3.49 percent between 1980 and 2011 led to half a million SCIE publications in 1990 and about 1.1 million new SCIE publications in the year 2011 alone.

Global Differentiation & Collaboration

It is generally recognized that recent unprecedented science productivity is partially a result of a significant rise in the volume of SCIE publications from scientists in a growing number of nations (UK Royal Society 2011). The ten countries that produced the most SCIE publications (in 1000's) in 2011 and their average annual growth rate between 1980 and 2011 are the United States (282, 2.63 percent), China (153, 17.61 percent), Germany (80, 3.35 percent), the United Kingdom (74, 2.99 percent), Japan (69, 3.60 percent), France (57, 3.31 percent), Canada (46, 3.80 percent), Italy (46, 5.79 percent), India (43, 4.80 percent), and Spain (41, 8.82 percent). What the SPHERE results show, which was not recognized earlier, is that these trends of global diffusion and regional differentiation began much earlier in the 20th century than commonly understood.

This is evident in the shift of the global center of gravity of SCIE publications over the century when calculating the annual weighted geographic centroid of each country by the number of SCIE publications produced in that country (see Zhang, Powell & Baker 2015). By 1900, the global center of SCIE production had already moved significantly west of the founding European centers of modern scientific inquiry. Early in the 20^{th} century, France, Germany, the United Kingdom and the United States largely dominated scientific production, with the last in marked ascendancy. Over the next 40 years, US universities, emulating the model of the German research university preeminent in the early 20^{th} century, became increasingly productive (Baker 2014; Geiger, 1986). But despite the victory of WWII and massive investments in higher education and science, American dominance began to decrease. Like the trajectory of the world's center of economic gravity (Dobbs et al. 2012), a new world pattern emerged in the middle of the century as the scientific center of gravity turned back east, beginning the trajectory it has charted for the ensuing 60 years.

Global competition for scientific impact is no longer solely an Atlantic battle but rather one that pits the superpowers—the US and China—against each other, along with the many less populous countries of Western Europe with their highly productive science systems. Although growth in SCIE publications significantly decreased in Japan during the 1990s, the rise of other Asian countries—in particular China and South Korea (which ranked 11th in 2011, with an annual growth of over 20 percent since 1980)—pulled the center of gravity further eastward across the North Atlantic during the past two decades, at a pace of about 0.90 degree per annum, passing the prime meridian in 2000. This dramatic change in direction is a function of both fast growth in East Asian countries and slowing growth (in fact: *relative* decline) in scientific production in the US, which has posted an average annual growth one full percentage point lower than the world average since 1980s.

International Collaboration

At the same time, there has been substantial and growing international collaboration, particularly from 1980 onward. Concurrent with the development of much science policy aimed at advancing national capacity to compete globally, collaboration by teams of scientists based in multiple nations not only increased after mid-century but entered an uninterrupted period of exponential growth from 1980. One-third of all research papers worldwide result from international collaboration and less than 26 percent are the product of one researcher alone. Indeed, the number of co-authored papers has more than doubled since 1990 and over a third have multiple nationalities sharing authorship. Obviously, the scientific landscape exhibits myriad linkages. Established economies collaborate more than rapidly growing scientific nations (e.g. China, India, Brazil), but growth is common to all countries (Adams 2013).

The well-documented rise of China and the newly-found scientific ambitions in the Middle East provide new opportunities for the production of science and for international collaboration. But lasting differences between countries are also unsurprising: “They reflect the strength of research, the availability of resources, and the scale of the research community in each country” (UK Royal Society 2011: 47). The proportion of all SCIE papers that have authors based in institutions from two or more countries—internationally collaborative papers—have also been growing rapidly (see Zhang, Powell & Baker 2015). Whereas in 1980, only about 2 percent of all SCIE publications were internationally collaborative, just three decades later, this proportion climbed eleven times. Currently, over one in five papers are internationally collaborative, driven by rising exchanges, the dominance of the English language, and Internet-based networks. More than ever, scientific production reflects not only regional competition but also—in an era of heightened global flows of academics and scientific knowledge within strengthened worldwide networks—the growing collaboration among scientists worldwide. As the investment in international branch campuses and knowledge hubs in the Arabian Gulf countries attest, more than ever higher education and science are becoming global enterprises in which cross-national and cross-regional collaboration are key sources of innovation.

The unprecedented, exponential growth in article production reflects the increased importance of science in countries worldwide. The shifting center of gravity away from the US emphasizes its relative decline as especially Asian and European countries heavily invest in their national higher education and research capacity. Simultaneously, the pursuit of cutting-edge knowledge production relies on building international and intercultural bridges between scholars. Thus, research and development requires *investment not only in individuals within organizations*, but also in the *networks, connections and exchanges that facilitate discoveries.*

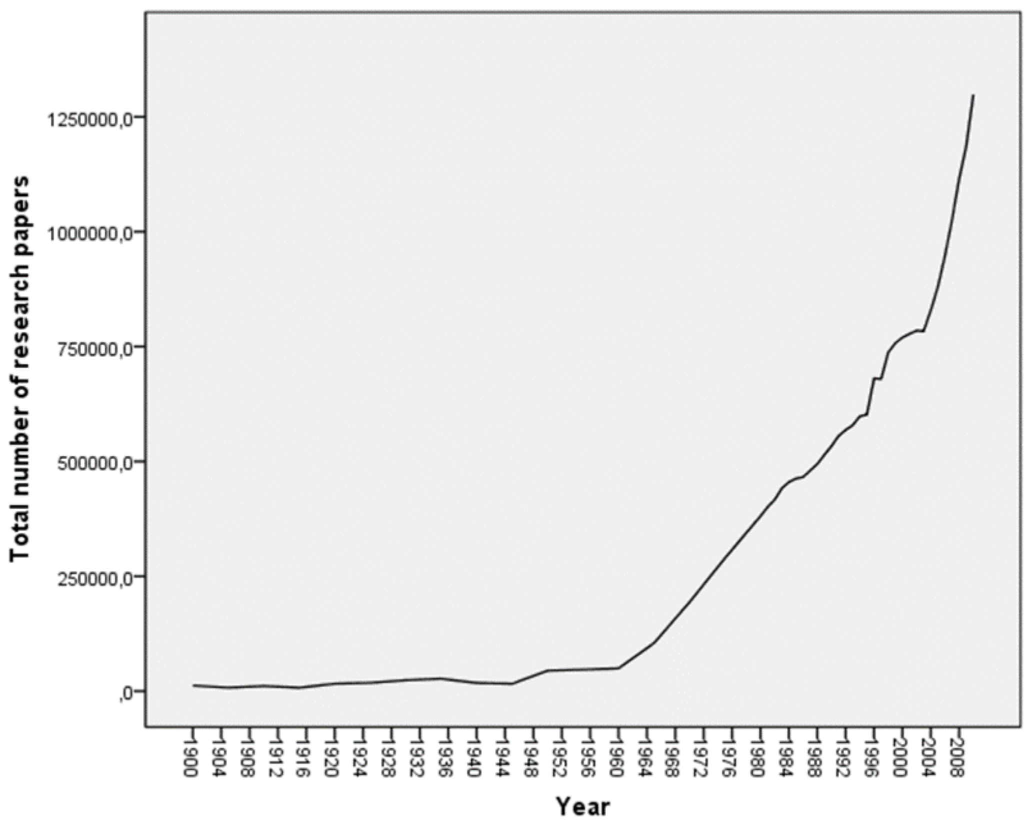
Connection Between Scientific & Economic Productivity

The concurrent shift and eastward movement of the centers of economic prosperity (Dobbs et al. 2012) and scientific production since 1950s are not surprising. The relationship is likely mutualistic: economic development provides resources necessary for scientific production, which in turn spurs further economic growth. Although no causality can be inferred from this concerted change, decades of economic research have convincingly shown that education, science, and technology have played crucial roles in economic growth (Solow, 1957; Romer, 1986; Goldin & Katz, 2009).

Investments in science and education are obvious explanations for the determination of scientific productivity. The most productive countries in the world of STEM+ are indeed the countries with high values of per capita GDP and high investments in science and education. While scientific giants like the US or China account for a high proportion of global scientific journal article production, the most productive countries on a per capita basis are a few smaller ones (e.g. France, Belgium, Switzerland, Israel, Scandinavian countries) (May 1997). These smaller research systems contribute importantly to scientific output and invest substantially in higher education and R&D. When adjusting for the size of population and the economy, the proportion of GDP spent on R&D, or the number of researchers, some smaller European countries are more productive than mid-sized or even large ones, allowing us to gauge global scientific capacity-building. Universities provide a much more prolific climate for research than extra-university research institutes (May 1997). The wealth of countries, measured by per capita GDP or other similar indicators has an essential impact on scientific productivity, but wealth alone does not explain the differences in scientific output.

As Figure 1 depicts, the overall development of world science as seen in the numbers of SCIE publications from 1900 to 2011 was close to an exponential line.

Figure 1: The Overall Development of the Number of STEM+ Papers Published Worldwide, 1900- 2010



Next to the massive rise in the number of overall papers, especially since 1960, another important phenomenon was the globalisation of science, with the numbers of countries contributing to this extraordinary total output also growing impressively. While in 1900 only 27 countries and territories were participating in the production of STEM+ papers, by 1950 this number increased to 36, in 1980 to 162, in 1990 to 173, in 2000 to 199 and in 2010 to 206–a nearly six-fold increase since the mid-20th century. The average number of papers produced by a country has also increased since 1900, from 416 to 1189 in 1950, 3779 in 2000. By 2010, the average number, 6262, had risen again by 65% in a decade. These numbers might nevertheless be somewhat misleading as the standard deviation for number of publications was very high and has also increased over the years.

If in 1900 the top ten countries in the world published 86.88% of all papers, in 1950 their proportion increased slightly to 90.57%, but by 2000 this had dropped to around two-thirds (68.86%) and by 2010 to only 63.18%. Thus, the share of production that smaller contributors make to world science has witnessed major development. The number of countries producing more than 0.1% of STEM+ papers in the world has increased from 18 in 1900, to 24 in 1950, and later to 38 in 1980 to 45 in 1990, 51 in 2000 and 55 in 2010. In fact, the huge increase in the numbers of countries involved in the production of science has occurred at the low end of the spectrum. In other words, most countries now contribute at least some STEM+ science published in citation index journals

Case Studies

In addition to the global, long-term historical analysis of SCIE data, we examined the relationship between university development and scientific productivity in key cases from around the world. These case studies employed a neo-institutional framework to explore and explain how the tremendous expansion of higher education and science across the world manifested in particular countries. They also adopted a mixed methods approach to analyze institutional models of higher education development and science capacity-building over time and the consequences thereof for scientific production measured in peer-reviewed papers. They are especially focused on the two organizational fields responsible for the vast majority of state-funded research, namely research universities and non-university research institutes of various sizes and in diverse associations, as well as other key actors. Read together, they demonstrate the considerable differences across time and space in the institutional settings, organizational forms, and organizations that produce the most research.

The analyses illustrate how differences in national models in developing research universities and institutes explain long-term cross-national trajectories in scientific productivity. Regarding the United States, the largest science producer for decades, we find that its world-leading capacity is built upon American mass higher education, especially since the Second World War. In Europe, our comparisons of higher education and research institutes show that these different organizational forms have contrasting contributions in Germany and France—traditionally top science producers—and neighboring smaller countries Belgium and Luxembourg. Despite the different relative significance of these organizational forms in each of these Western European countries, both are crucial to overall scientific productivity. Our research on South Korea shows the significant contribution of private universities and investments to the fast growth of that country's higher education and research system. Qatar, one of the most rapidly-growing countries anywhere in the world, developed a comprehensive national research system within fifteen years, further evidence of the capacity of certain smaller, well-resourced states to out-perform the traditionally (quantitatively) dominant states when scientific productivity is standardized.

The remainder of the report summarizes case study analyses undertaken by project investigators. Cases include China, the United States, Western Europe (a comparison of Belgium, France, Germany, Luxembourg), Germany, Japan, South Korea, Taiwan, and Qatar.

China

This summary presents a thorough historical overview of policies that have governed and guided scientific research in China since 1949, followed by an analysis of Science Citation Index Expanded (SCIE) publications data to illustrate changes in scientific publication rates concurrent with these policy reforms and programs.

An historical review. We divide the historical period since 1949 into four stages, each with distinct R&D policies. During the first period (1949-1955), the newly established communist government finally had a chance to build the nation along a self-chosen socialist track. During this period of time, China restructured its higher education system and built a new S&T workforce. In particular, China modeled itself after the Soviet Union, and benefited greatly from its assistance. During the second decade, China made some developmental progress in S&T despite fluctuating policies. Progress was made not only in terms of quantity, but also in terms of quality; by 1965, China had many high level scientists whose achievements were meeting a world standard of excellence. During the Cultural Revolution (1966-1976), however, scientific activities came to a halt. Instead, politics and class struggle became the main theme of people's lives. Leftist policies completely reversed the policies set up before 1966 for maintaining the independence of scientific work and respecting intellectuals and learning from foreign countries, and did irrevocable harm to science and education.

In the fourth period since 1978, a series of R&D policies enacted during this period have promoted impressive achievements in science and technology. During 1980s, three S&T development plans were especially notable, including the “Spark Program”, the “863 Program”, and the “Torch Program”. In May 1995, the government announced its Decision on Expediting Progress in Science and Technology, based on a strategy of “revitalizing the nation through science and education.” To accelerate S&T development, higher education institutions were evaluated and re-endowed. Among various efforts and initiatives, the “211 Project” and “985 Project” were most notable, with the goals to build national elite universities by improving their capacity in teaching, research and public service. Meanwhile in recent decades, large scale polices (e.g., “100 Talents” and “1000 Talents” programs) have been adopted to attract prominent scientists and world-class researchers from around the globe.

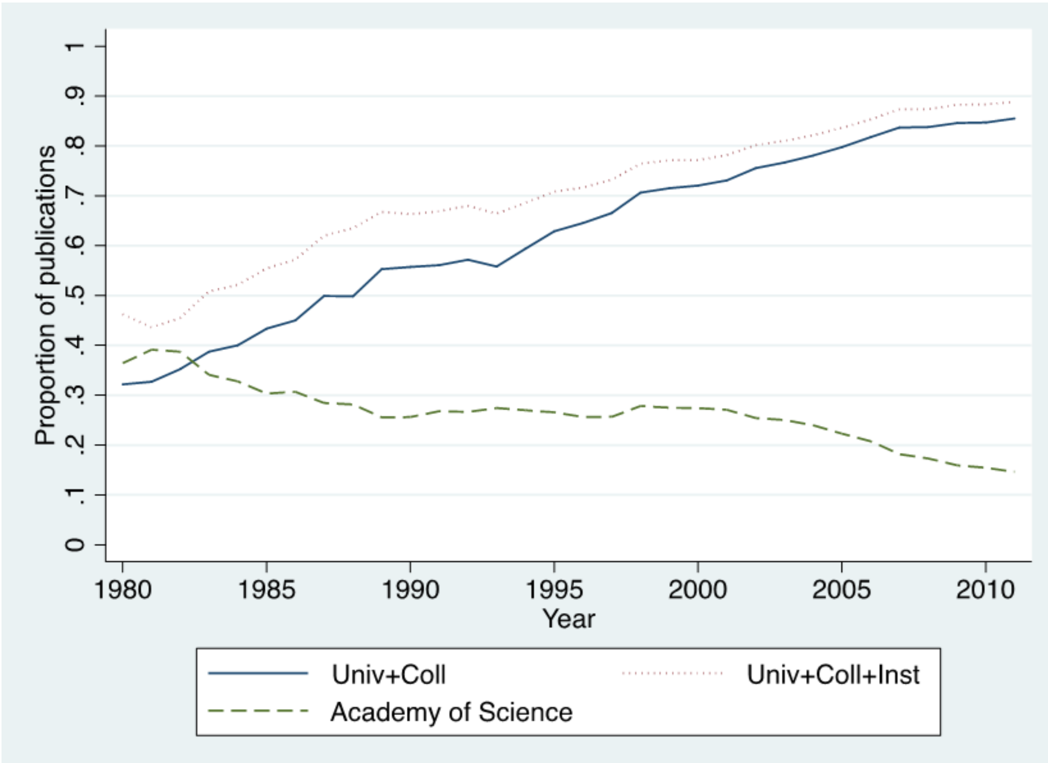
Science production from China. Between 1980 and 2011, the total number of publications from China (including Hong Kong and Macau) has increased more than 150-fold, averaging over 18% annual growth. The gradual growth in publishing activities came right after the reform and the adoption of an open-door policy in 1978. For the first 15 years after 1980, growth was gradual. The proportion of world SCI articles authored or co-authored by researchers from China grew from essentially zero (about 0.2% to be exact) to about 2% in 1995. This modest growth increased significantly over the next 5 years. In 2000, Chinese researchers authored or coauthored about 3.3% of world SCI articles. Since then, the proportion of world SCI articles authored or coauthored by Chinese researchers has been increasing at about 1% per year, culminating in an impressive 13.7% in 2011.

Chinese Academy of Science and other higher education institutions. A discussion about scientific research in China would not be complete without examining the role of the Chinese Academy of Science (CAS), which is, historically, the single most prolific research institute in

China. Figure 1 clearly shows the changing landscape of scientific research over the past 30 years or so. CAS produced about 40% of all research articles from China, but this proportion has been decreasing over time, especially from 2000 to 2010. In 2011, the proportion of articles produced by CAS decreased to about 15%. Not surprisingly, during the same period of time the higher education sector has played a more prominent role; in the 1980s, higher education institutions (not including CAS) produced about 40% of all articles by Chinese scholars, but in 2011, they produced approximately 85%.

Policy recommendations. The central theme from our policy review and data collection is that the higher education sector in China is a centralized system; it is an important part (and thus serves the interest) of national development. A centralized system has its pros and cons. When well planned, it mobilizes limited resources and maximizes overall output. There are, however, many downsides of a centralized system. However, the system is also prone to catastrophic failures, because there are no checks and balances built into the system. Being a centralized system also means that higher education institutions have been quite responsive to the common goals set by the central government. The recent surge in SCI publications can be seen as a response to incentives provided by the central government. What is measured tends to be accomplished; however, not all goals can be easily achieved. Although the recent grand scheme of constructing "world class universities" has ushered in a period of dramatic growth in scientific research as measured by the quantity of SCI publications, the quality and originality of these publications have not kept pace, which raises the question whether growth in scientific research in China can be sustained in the near future and whether Chinese universities can truly become "world class" before these imbalances are satisfactorily addressed.

Figure 2: Proportion of Publications by Scholars from the Chinese Academy of Science and Other Higher Education Institutions



United States

The United States currently has the highest number of super research universities (Mohrman, Ma & Baker 2008; Baker 2014), and these institutions produce considerable amounts of new knowledge across many fields (U.K. Royal Society 2011; See Figure 3). American-based scientists historically and contemporary produce the largest share of STEM articles worldwide, though China is catching up quantitatively very quickly. Three trends, we argue, are symbiotically responsible for US science production: firstly, inclusive mass secondary and higher education throughout the 20th Century, culminating in an extensive system of doctoral degree training in STEM+ fields (see the red, purple, and green trend lines in Figure 4); secondly, decentralized higher education policy (or even "non-policy"), yielding high levels of university creation and competition; and thirdly, high levels of societal legitimation (e.g., national scientific societies, represented by the blue trend line in Figure 4) and hence private funds in the higher education sector that diversify the resource base for higher education and science. The American case emphasizes the contribution of large public universities (which epitomize these three interrelated trends) to both science production and science capacity building. While we focus on the factors leading to this coincidental model and its subsequent influence internationally, further research will need to explore the challenges to its sustainability in the future.

Figure 3: Percent of U.S. STEM+ Publications Produced by University Authors, 1900-2011

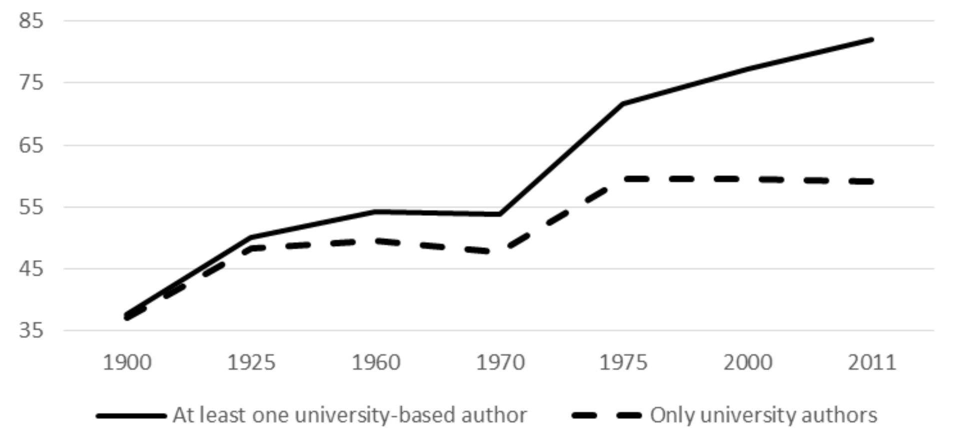
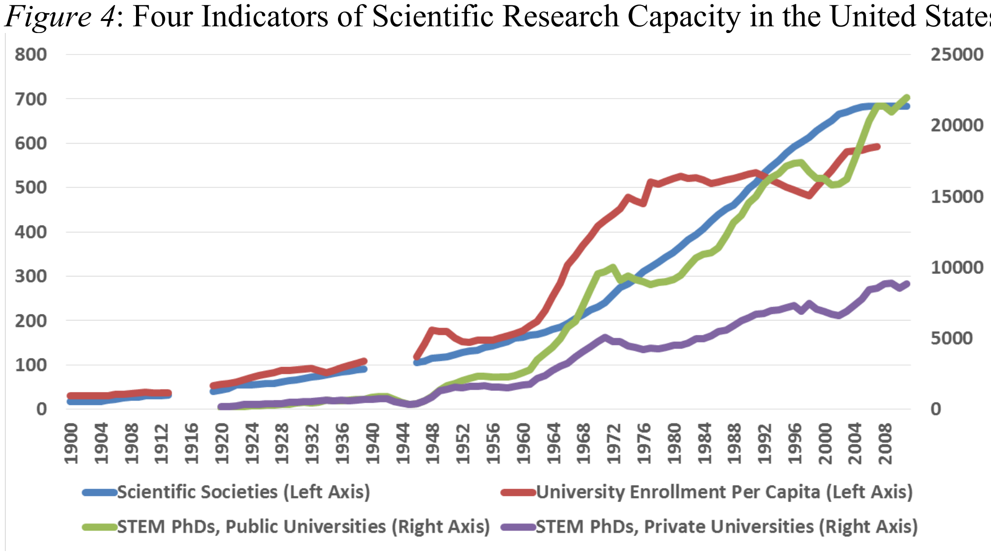


Figure 4: Four Indicators of Scientific Research Capacity in the United States, 1900-2011



Western Europe (Belgium, France, Germany, Luxembourg)

All countries invest in higher education and research. Smaller states often focus on a single national university, larger ones on a range of universities and often highly-differentiated systems of universities and extra-university research institutes. They invest considerable sums in science and education and contribute to global science by publishing vast numbers of papers. However, since the world has many smaller countries than larger nations, research should also examine these. To contrast the development of higher education and research in Western Europe, we selected two larger nations (Germany, France) that have traditionally contributed hugely to global science, and two smaller countries (Belgium, Luxembourg). Comparing both growth over time and the symbiosis between the institutions and organizations of higher education and research within Western Europe, we focus on such national developments within global higher education and science to reconstruct the overall scientific output in selected STEM+ disciplines over the 20th Century in these four countries. While ever more countries contribute to global scientific output, most science is still produced by relatively few countries, many in Europe. While unsurprising that major science producers like Germany contribute a large share, smaller countries are often more productive on a per capita basis. Comparing in-depth these four European countries manifests differences in scientific productivity that reflect contrasting institutional settings (combinations of research universities and independent institutes) in which peer-reviewed research is created. A commonality among all of these countries in Western Europe is the emphasis on the research university as the key organizational form contributing to scientific productivity. A good recent example is Luxembourg, where the establishment of a national research university in 2003 facilitated a rapid rise in production during the following years.

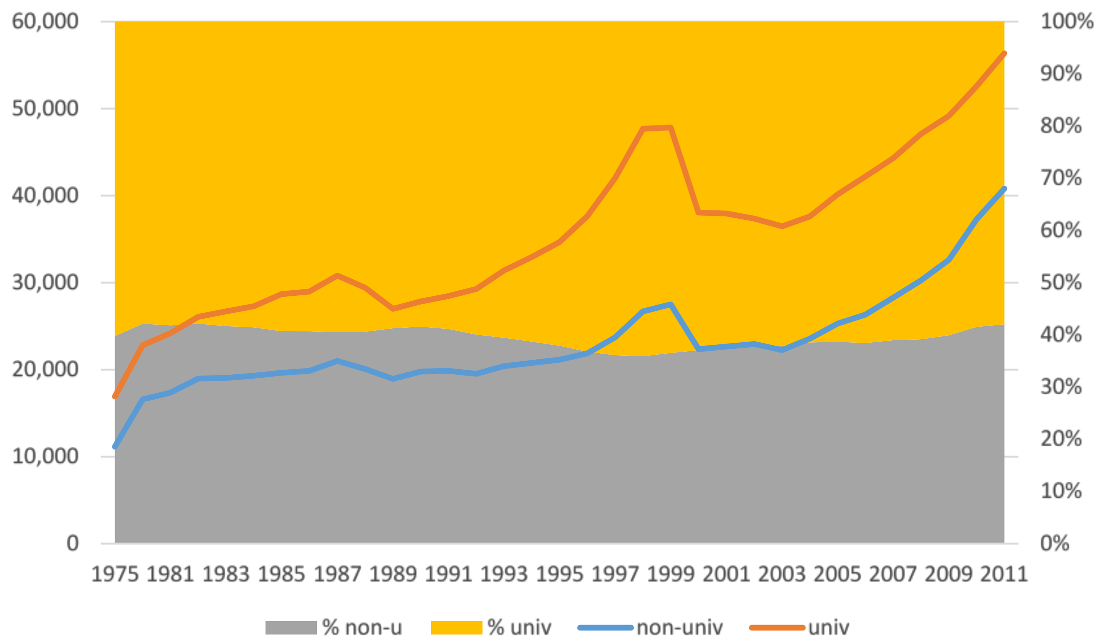
Germany

Germany has been an engine of both higher education and science development for over a century and half, yet has declined from the dominant science nation (and language) to a top-ten producer of natural science. Investigating the long history of its evolution, the foundational principle of the research university is and continues to be the nexus of research and teaching. First established in Germany and spreading globally since, this idea and the resulting organizational form—with its philosophical faculties, seminar, academic self-governance—led to Germany's pre-eminence in university-based modern science. This university type continues to dominate German higher education, despite establishment of more praxis-oriented universities of applied sciences. These organizations, part of global academic drift, reflect the upgrading of vocational and professional schools in terms of curricula and certificates.

Yet Germany not only gave birth to the research university with its strong philosophical faculties eventually representing the entire breadth of contemporary science disciplines—but also paved the way for massive tertiary educational expansion with its scientifically-oriented secondary teaching that substituted for undergraduate teaching. Germany also contributed to the exponential rise of science by establishing extra-university research institutes, often collaborating in large associations, devoted to pioneering science in specialized fields. Thus, university-based research capacity in Germany is only half the story, as the hundreds of associated research institutes flourish in all parts of the country, funded as they are by the Federal and state (*Länder*) governments.

Examining the scientific output of Germany in 2010 in terms of SCIE publications (see Figure 5), it is thus no surprise to see a mix of research institutes and leading research universities. These two strong pillars of research capacity in Germany have grown substantially, but their proportion has remained relatively constant from the mid-1970s to 2011.

Figure 5: Scientific Productivity in Germany: Universities vs. Non-Universities, 1975-2011



(left: number of absolute publications; right: proportion of univ./non-univ.).

However, this duality has been maintained during an era of the underfunding of universities, which remain significantly dependent on the state—far more so than universities in the UK and US, for example, that rely on variegated sources of income (though here, too, the state has cut its support to higher education, in effect privatizing this level of education). Charting institutional change on multiple levels, from the systemic and organizational to interactional, we show how the ensuing dual structuring of universities and specialized extra-university research institutes affects research capacity: these two pillars of research capacity have ensured that Germany continues to be among the handful of top science producing countries, yet several smaller countries are investing more and also achieving higher rates of scientific productivity per capita (see below).

Instead of questioning how these organizational fields might cooperate more and thus retain or extend their competitiveness, policymakers have, in recent reforms such as the

"Excellence Initiative," failed to adequately address the essential investments needed. Instead of bolstering the research capacity of universities of applied science (and giving these organizations the right to confer doctorates), interest groups aim to maintain or even strengthen higher education stratification (making the peaks higher) without sufficient funding of the system as a whole. Indeed, Germany may not have any top-ten or top-twenty universities in global rankings, but a considerable number in the top 100, reflecting the relative equality of research-oriented universities throughout the country. Other European countries have also implemented policy reforms that aim to identify a select number of leading universities that then receive additional (albeit quite limited) performance-based funding. Future analyses are needed to determine whether these programs and targeted investments have been beneficial.

The institutionalization of this complex science system reflects choices made a century ago as the country rebuilt after World War I and the massification of higher education after World War II. This expansion proceeded without the necessary investments to carry on the tradition of high-level, research-based education for all students accepted to universities that, despite the Bologna Process (and its three-cycles of BA, MA and PhD), continues to emphasize graduate-level training, with the majority of students transitioning directly on to the MA-level after their first degree. Whether Germany could have maintained its status among the very most productive science countries without splitting its R&D investments in half remains to be answered. Today's discoveries rely, as ever, on both pillars: strong research universities and elite extra-university research institutes. In Germany, research and development policies finance a complex higher education and science system that has consistently been among the most significant worldwide.

Japan

The number of published articles in the United States rose from 1975, as the U.S. became a global center of research. The number of articles also rose in the United Kingdom, Germany, France and Japan from 1975 to 2000. In Japan, however, the number of articles increased more rapidly than in the United Kingdom, Germany, and France over the same period (1975 to 2000). While the U.S. continued to raise its level of article production through 2010, Japan is the only country that did not increase the number of the articles produced from 2005 to 2010. As a result, Japan went from being the second largest knowledge producing country in 1990 to the fifth in 2010.

The university system, and especially the national universities, is the core of knowledge production in Japan. National universities increased the number of articles they produced, even though their share of published articles fell from around 60% in 1975 to around 45% in 2010. Private universities grew the number of articles they have produced from 1975, but their share of total Japanese articles produced was still less than 15% in 2011. Others producers, including business enterprises, make up the second largest group of producers, but the number of articles they produced decreased between 2000 and 2005.

Former imperial universities have been the leading producers among the national universities with the highest increases in article production, even though their share decreased until 2000. After that, imperial universities again started increasing their share. Pre-World War II universities all increased their overall amount and share of article production until 1990. Their share was stable after that. Post-WW II universities 1 and 2 have also been increasing their number of articles and their share of articles until 2000, before their shares started decreasing or remaining the same from year to year.

In summary, top national universities (former imperial university & pre-WW II universities) have been the biggest scientific producers, but the second tier national universities (post-WW II universities 1 and 2) sustained the world ranking (No.2) of scientific productivity into the 2000s. Not surprisingly, as funding from basic governmental block grants and expanding competitive funds decreased, article production at second tier universities also decreased or stagnated. These findings call into question the widespread belief among education and scientific policy-makers that "competition" and "selection and concentration" are inherently beneficial for scientific productivity. Secondly, second tier national universities are clearly vulnerable to market forces and benefit significantly from government funding.

Figure 6: Changes in Number of Articles Produced in Japan by Organization Types, 1975 to 2010

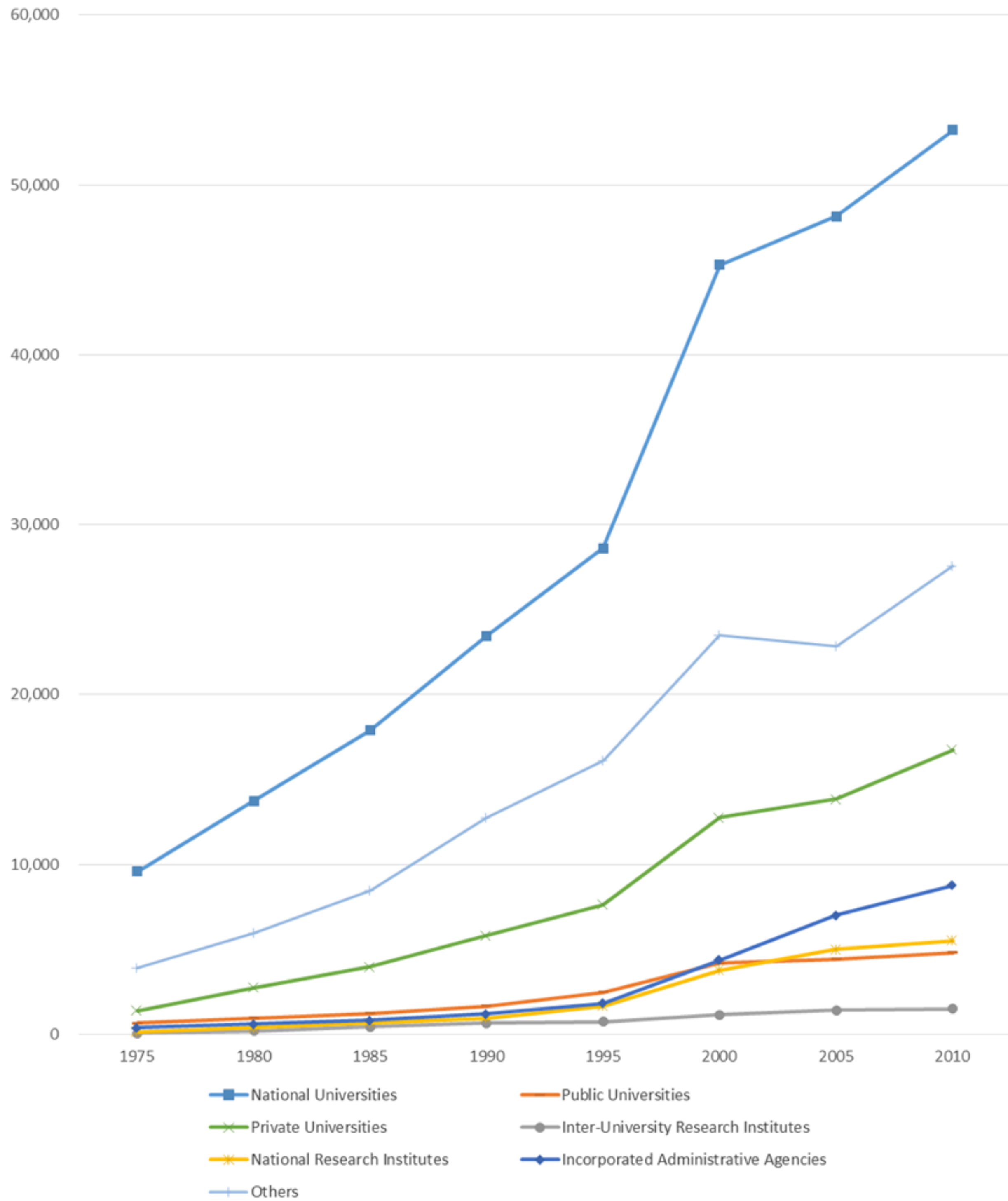
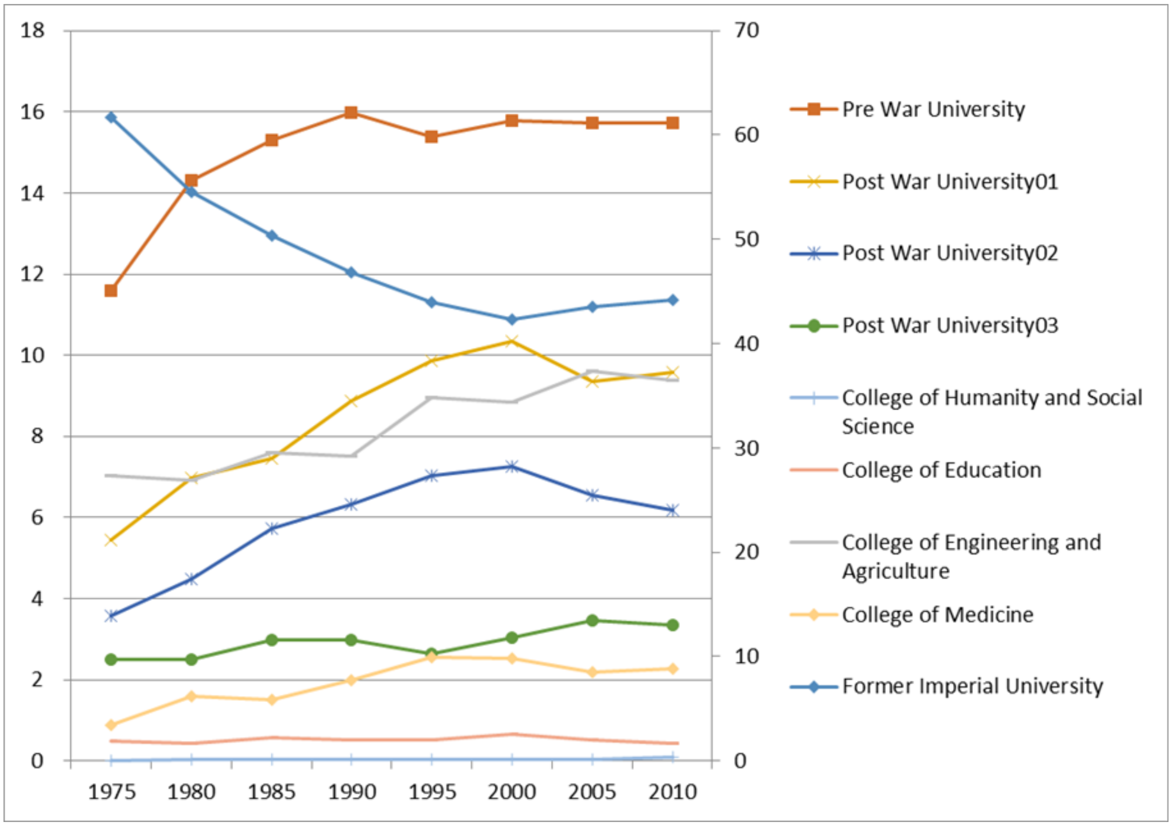


Figure 7: Changes in the Percent Share of Articles Produced in Japan by Types of National Universities, 1975 to 2010



Note: The second Y axis (on the right side of the figure) is used for Former imperial universities.

South Korea

Higher education has been a key foundation for South Korea's rapid economic development. However, unlike many other countries, the growth of Korean higher education was heavily dependent upon private institutions or investments rather than state funding. In order to investigate how private universities have contributed to the growth of Korean higher education and research, it is necessary to (a) compare student enrollments in private universities to public universities over time (with OECD and other data); (b) compare science production at private universities to public universities over time (SPHERE data); and (c) compare science production of private and public universities in Korea to those in Japan (SPHERE data). In higher education, Japan is thought to be similar to South Korea not only because of its proximity, but also because both countries see high enrollment rates in private higher education institutions.

In Korea, education is considered a significant avenue of development not only for individuals, but also for society. However, the government has been unable to build or operate additional national or public higher education institutions (HEIs) sufficiently to meet the high demand for higher education among Korean families. Because of these constraints, the government has been relatively open to the establishment of private HEIs as an alternative. Table 1 shows how dramatically the number of private HEIs and students enrolling in them has surged from 1965 to 2010. This is largely a result of relevant government policies, such as a temporary graduation quota system from 1980 to 1987, which succeeded in increasing higher education student enrollments but failed to limit the number of qualified graduates.

Research is a relatively new mission for Korean HEIs. Until the 1980s, Korean government and society saw colleges and universities as a place to provide human resources for national industries, but not a place for scientific research. During that period, research was synonymous with the production of new merchandise or new technology for industry. For example, even though about 90 percent of R&D expenditure of Korea was used by either companies or research institutes, less than 10 percent of SCIE articles were published by those sectors.

In addition, research has been conducted mainly by national universities, not private ones, until the late 1990's. A few private universities began to develop research capacity with the support of the Korean government from the early1990's. With the implementation of Brain Korea 21 (BK 21), the production of research articles by Korean private HEIs surpassed that by national/public HEIs. Most of the regional national universities (except for Seoul National

University) refused or hesitated to participate in the BK 21 program because they objected to the preference it gave to private institutions in the capital area. In contrast, most private universities were proactive in seeking Brain Korea 21 funds.

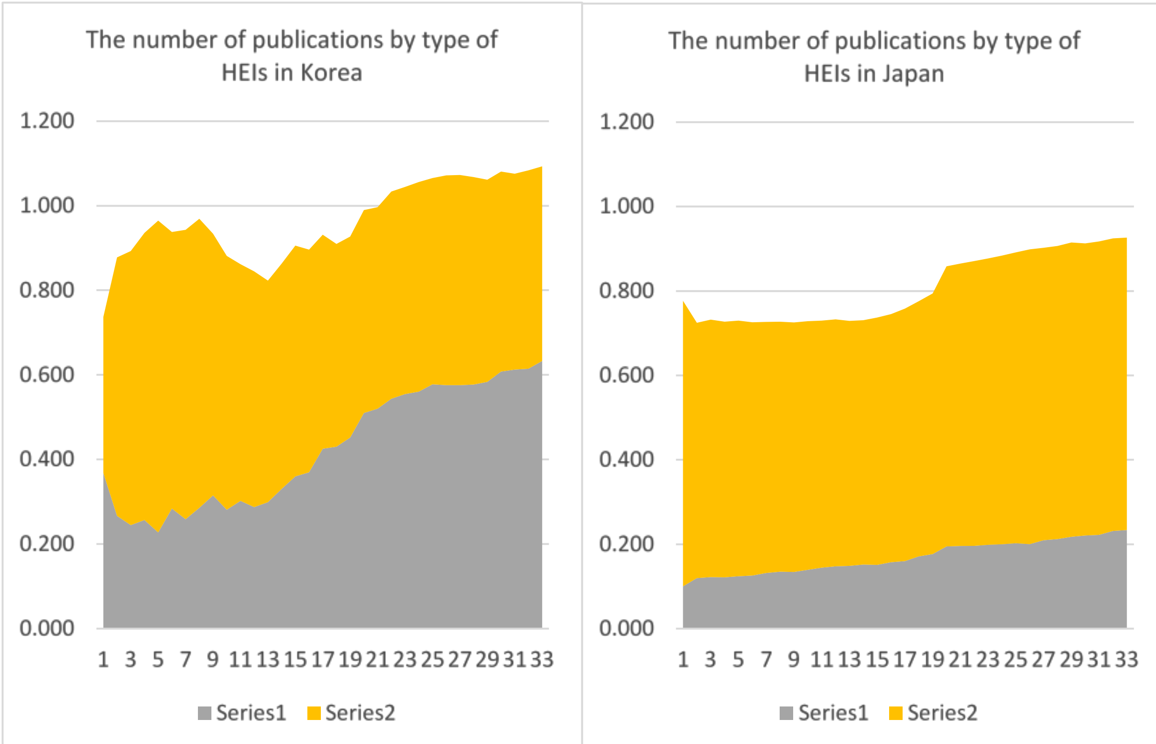
Despite the similarities in private higher education enrollment, Figure 8 shows that publications by Japanese private HEIs never surpasses that by national and public HEIs in Japan, and the gap has persisted in the past 30 years. In Korea, however, the proportion of publications by private HEIs exceeds that of national and public HEIs from 1998, and the difference between the productivity of these two sectors continued to grow slowly since then. This challenges conventional wisdom that national or public HEIs are better suited to basic (and less profitable) scientific research because of their orientation to the public interest, while private HEIs are more sensitive to market forces.

Table 1: Korean Higher Education Institutions and Student Enrollments by Type of Institutions

year	Number of HEIs				Number of Students enrolled in HEIs			
	Private	Nat/Pub	% Prv	% Nat/Pub	Private	Nat/Pub	% Prv	% Nat/Pub
1965	112	50	69.1%	30.9%	100,183	37,611	72.7%	27.3%
1970	100	42	70.4%	29.6%	120,460	50,896	70.3%	29.7%
1975	83	33	71.6%	28.4%	159,253	65,596	70.8%	29.2%
1980	169	67	71.6%	28.4%	421,377	146,678	74.2%	25.8%
1985	205	50	80.4%	19.6%	925,139	284,508	76.5%	23.5%
1990	207	51	80.2%	19.8%	1,106,231	297,667	78.8%	21.2%
1995	272	55	83.2%	16.8%	1,507,161	724,005	67.6%	32.4%
2000	310	62	83.3%	16.7%	2,262,559	871,553	72.2%	27.8%
2005	359	60	85.7%	14.3%	2,432,194	834,309	74.5%	25.5%
2010	359	52	87.3%	12.7%	2,518,456	809,069	75.7%	24.3%

* Data from Statistical Yearbook of Education (each pertinent year)

Figure 8: Number of Publications by Type of HEIs in Korea and Japan



Taiwan

Taiwan is a relatively small country among this group of case studies, and it illustrates the advantages and challenges that smaller nations face. With an overall population of about 23.4 million, Taiwan has one of the most intensely schooled populations in the world. There are 165 universities and college accommodating 82% of the school-age population, about 1 million (MOE, 2014). Even though its scale is comparatively small, its research power is considerable. In 2013, Taiwan registered 11,598 patents at the US patent office, making it the fifth highest patent producer in the world (USPTO, 2013). According to SCIE data, Taiwan produced 32,018 papers in 2011. These achievements make Taiwan a global hub of technology innovation. To fully appreciate the development of technology innovation in Taiwan, it is crucial to understand the rise of Taiwanese universities.

Historically, the development of higher education and science capacity-building is interesting in its focus on a centralized, mainly publicly-funded system. As one of the key components in the national innovation system, universities have always been a priority concern for policymakers, especially during the implementation of a new national strategic plan for development. In the 1980s, Taiwan concentrated its limited educational resources on investment in universities and used the technology developed and graduates educated in universities to give birth to the high technology industry. The Hisnchu technology park, comprised of two research-intensive universities and a cluster of high technology companies, was the hallmark of this era—and is now well known as one of the world's leading areas of semiconductor manufacturing.

Figure 9 shows that, in 1975, universities only produced 136 papers, accounting for 55% of Taiwan's entire journal article production. By 1990, it had produced 1,686 papers, accounting for 66% of all articles. For the following two decades, universities led a national system of innovation in the pursuit of basic research. After the 1990s, universities maintained this leadership role in scientific production and even accelerated the pace of production. This development resulted from the expansion of higher education system. The massification of higher education allowed universities to accommodate more researchers and expanded student enrollment. This policy change created an excellent base for the development of human resources in science and technology. During the period 1990-2011, the number of research scientists increased about four times from 46,071 to 173,654. In 2011, the number of researchers per one thousand employees in Taiwan reached 16.2, surpassing 13.3 of Japan; 12.1 of Germany; 7.69 of South Korea (OECD, 2013).

In addition to the expansion of higher education, internal changes within the university sector also spurred the scientific production. In 1997, a new policy of faculty promotion was implemented nationally. Shifting from seniority-based to merit-based, the new promotion system emphasized the contribution of faculty to knowledge production. The government successfully cultivated a “publish or perish” culture among Taiwan’s faculty, and competition among faculty for research funding became much more intense. For example, official statistics shows that between 1994 and 2010, the amount of faculty competing for individual funding from National Science Council increased significantly. As NSC’s research funding budget increased, the approval rate for funding submission declined from 80% to 43%.

The year of 2000 was another milestone for policy change. Threatened by the research university policy adopted by China, Japan and South Korea, Taiwan crafted its first competitive institution-based project aiming to forge excellence among research centers at universities. Soon after, this project was replaced by the more ambitious project World-Class University Project, which eventually provided a decade’s worth of funding for a select group of 12 research-intensive universities in Taiwan.

Rather than individual competition among faculty, these programs stimulated competition among institutions. Several strategies for competition were adopted by the leading universities and eventually became common practice nationally—such as choosing cutting-edge research topics, organizing researchers into clusters, crafting international research teams, inviting distinguish scholars as project leaders, and recruiting Ph.D. holders graduating from top global universities as faculty. These practices changed the way universities conducted research and significantly enhanced their research power. Referring to Figure 9, after 2000, universities continued dominate scientific journal article production. Moreover, the quality of papers has improved. For example, most papers were published in journals with an impact factor in the top 20% and 40%, which indicates that the influence of research conducted at Taiwan universities became worldwide (see Figure 10).

Despite these successes in science-capacity building at Taiwan universities, there are still systematic problems that need to be addressed. One of biggest challenges has to do with the university system's funding structure. Taiwan universities heavily rely on public funding. This makes research projects at universities vulnerable to government austerity measures, and also reduces incentives among researchers to pursuing technology applications that result from research. This situation leads to concerns in some corners that government funding of universities threatens Taiwan's innovation ecosystem in the long run. One solution for policymakers is to introduce an additional matching funds system that encourages universities to pursue long-term partnerships with industry. This would leverage the government's limited research funding, improve the prospects for technology applications, and presumably, promote the sustainability of the national innovation system.

Figure 9: Scientific Productivity of Higher Education Institutions in Taiwan, 1975-2011

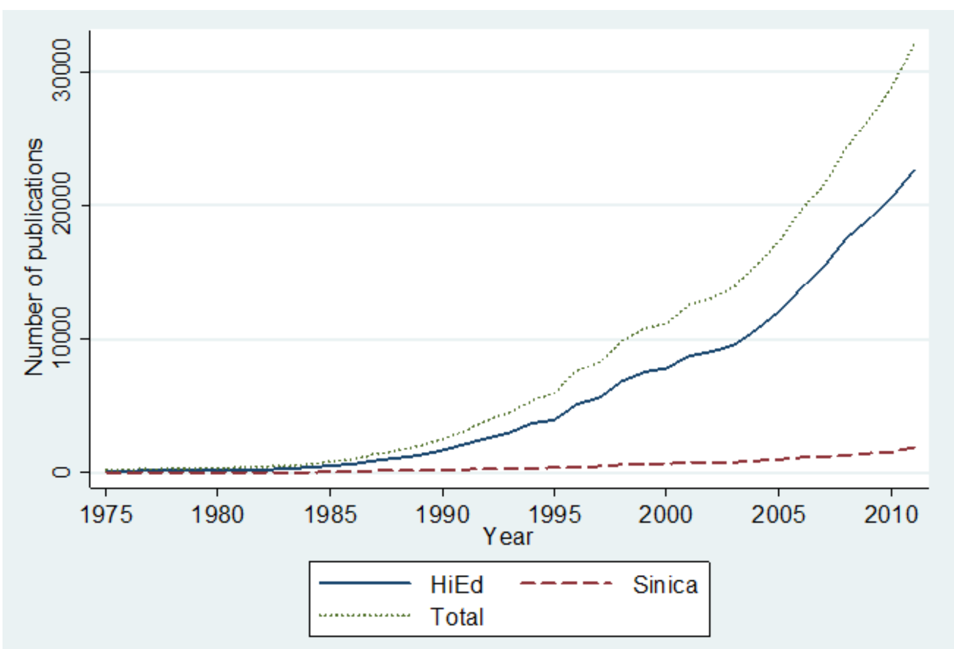
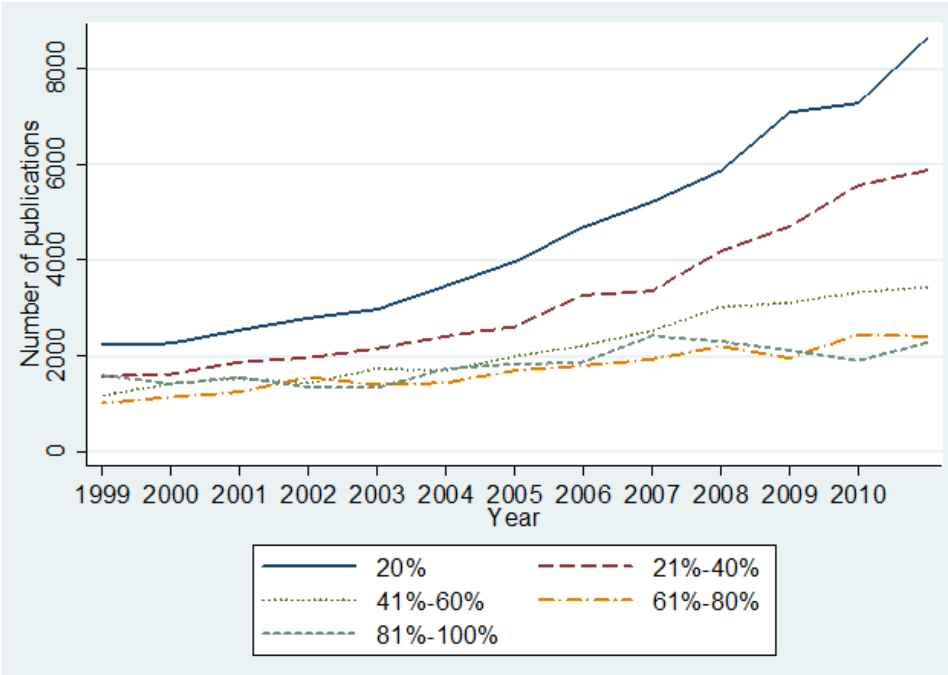


Figure 10: Relative Prestige (Impact Factor) of Taiwanese Publications, 1999-2011



Qatar

Qatar's higher education system has grown rapidly, and Qatar is at the forefront of a contemporary renaissance in science across the Arab and Islamic world. In January 2015, Times Higher Education released the first ranking of research universities in the Middle East and North Africa—Texas A & M's branch campus in Qatar was ranked number one in the region, above much older and distinguished institutions in Egypt and Lebanon. Qatar University (the national university) was fourth in the rankings (Havergal 2015).

This is a remarkable achievement because, among the case studies considered in this project, Qatar has the youngest higher education sector by far—and a unique one. The first and only national university was established in 1978, shortly after formal independence. Twenty years later, Qatar franchised the development of higher education to international branch campuses (Crist 2015; Powell 2014). By 2015, Qatar hosted twelve branch campuses of American and European universities. The development of the higher education sector in this novel fashion was tied to a national development plan that envisions a transformation of the economy away from dependence on hydrocarbon resources toward a “knowledge economy” by 2030; and a strategy of “knowledge diplomacy” that, coupled with other policies, intended to make Qatar a global education hub to enhance Qatar’s global visibility and reputation as well as further integrate its economy with key security guarantors like the U.S. and U.K. At the same time, this rapid and remarkable expansion of higher education in Qatar unifies two common strategies in capacity-building attempts worldwide (Powell 2014a, 2014b, 2015; Crist 2015): Firstly, Qatar seeks to cultivate human capital domestically through massive infrastructure investment and development of educational structures, including the national university (Qatar University); Secondly, Qatar seeks to match the strongest global universities through direct importation of existing organizational capacity, faculty and staff, and accumulated reputation.

Qatar is also the latest entrant into the global competition of science productivity among the case studies. The first scientific journal article attributed to at least one author with a Qatar-based affiliation appeared in 1980 in the SCIE database. Between 1980 and 2002, well under 50 journal articles per year on average were recorded for Qatar-based authors (see Figure 11). In 2003, the number of articles broke the 50 per year watermark and began a period of steep increase, reaching 366 articles in 2011 (the last year for which we have data). While these figures are tiny in comparison with the world’s larger research economies, this is nonetheless an especially notable achievement because of the short period of time in which it occurred. The national research system in most societies has evolved over decades (or in a small number of cases, centuries) and involved gradual integration of system units into a whole. In contrast, because of its wealth, Qatar has built a national research system—including institutions of higher education, scientific laboratories, and independent research institutes—in less than fifteen years. This approach can be considered a "compression" strategy, one that replicates the essential organizations associated with a national research system and compresses them into rapid, purposeful construction to create a new system where none existed before.

The principal finding about growth in scientific journal productivity in Qatar is that it unfolded almost entirely in partnership with global, non-Qatar based research institutions. In fact, scientific productivity exclusively published by Qatar-based research institutions remained constant between 1980 and 2011, with only marginal signs of increase in 2010 and 2011 (when the number of articles published in that sector exceeded 50 per year slightly).

There are three forces that account for the steep increase in scientific journal productivity from 2003. These consist of increases in the size of the scientific labor market in Qatar, in funding for scientific research, and in the number of organizations capable of conducting scientific research. The importation of a large number of international branch campuses substantially increased the number of PhD researchers based in Qatar. Qatar University and Hamad Medical Corporation, the institutions with the largest number of publications in SCIE, also embarked on aggressive campaigns to recruit faculty, researchers, and clinicians from outside the country as early as 2007. The majority of these researchers was in the natural and medical sciences and trained in the United States and Europe (and in the Middle East to a lesser extent). Not surprisingly, they maintained their professional association with non-Qatar based colleagues and research institutions for a variety of reasons, such as involvement with ongoing research projects, the advantages of continued engagement with active research environments, and the likelihood of eventual return to non-Qatar based research employment. Qatar's dependence on an imported, foreign scientific labor market naturally resulted in a high rate of international collaboration in its scientific productivity.

Secondly, the government of Qatar committed substantial sums of money to promoting scientific research. In 2007, it sanctioned Qatar National Research Fund, expressly modeled after the U.S. National Science Foundation, to fund scientific research in Qatar in service of the national interest. Within a few years, QNRF awarded about $150 million USD to scientific research annually, although that figure has dropped substantially in recent years. (About $90 million USD was committed in 2015.) Then in 2009, the Emir of Qatar declared that 2.8% of Qatar GDP would be devoted to R&D annually. Based on World Bank figures for Qatar's GDP in 2009 ($97.8 billion) and 2013 ($203.2 billion), that amounts to annual investments in R&D starting at $2.7 billion in 2009 and rising in 2013 to $5.7 billion. (As Qatar does not currently report public expenditures for R&D, it is not possible to verify actual amounts or categories of expenditure.) In 2013, $5.7 billion accounted for nearly 27% of total estimated public expenditure (BQ staff 2013).

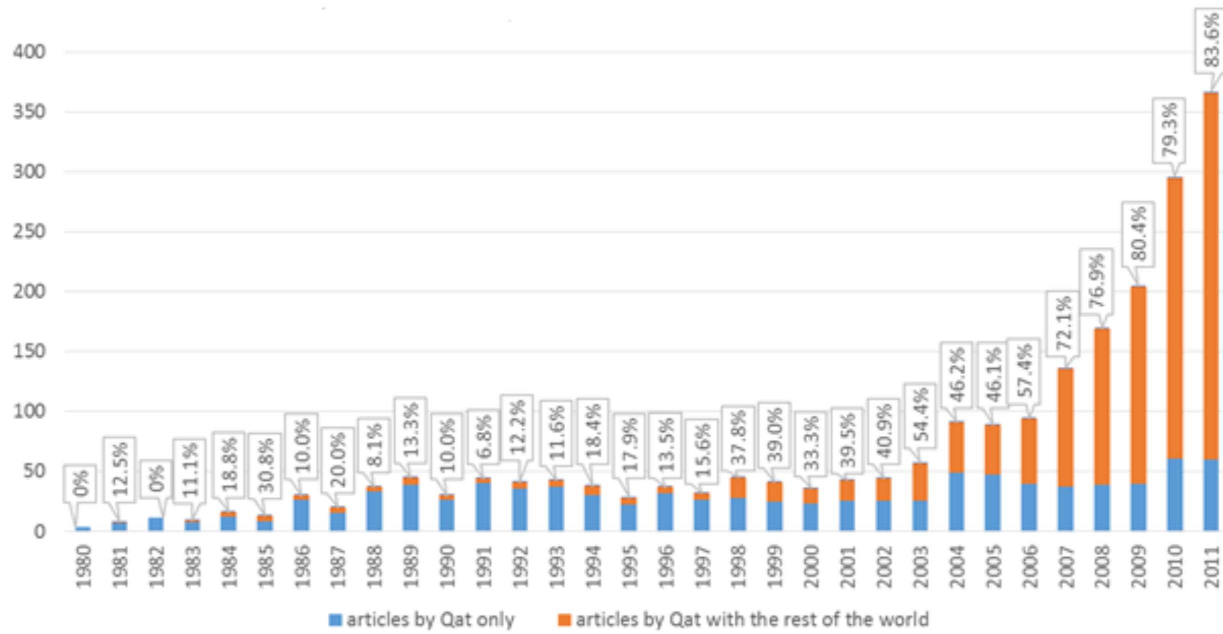
Importantly, this investment quickly increased Qatar's research capacity. In addition to direct funding for research activity, there were new laboratories, new equipment, more Ph.D. researchers, more technicians, more contractors, and so forth. While Qatar's scientific journal productivity was on an upward trend prior to the aggressive R&D funding strategy it began in 2007, this investment created an environment in which scientific activity could flourish, and for reasons both direct and indirect, fueled the rapid increase in its scientific journal article productivity since 2003.

Given Qatar's dependence on foreign scientific labor, high rates of international collaboration in its scientific journal article productivity will persist for a long time. But the marginal growth in Qatar-only article productivity since 1980 poses challenges for Qatar's leadership and suggests that developing Qatar's internal capacity for research activity—independent of partnerships with global research institutions—ought to be a high priority for

R&D policymakers in the coming years. Leadership in the R&D field and higher education has begun to address this need. QNRF's pursuit of global science is an interesting case in point. From its first international competition, global research institutions were eligible to apply to QNRF, as long as they had a Qatar-based institutional partner and that no less than 51% of the project labor and 65% of the project budget was conducted in Qatar. Despite these limits, QNRF explicitly encouraged collaboration with international research partners by assigning extra points in its review and selection process to projects with external collaborators—a policy that succeeded in spades, as demonstrated in the SCIE data. In 2014, QNRF dropped this policy and now assigns extra points to boost collaboration among Qatar-based institutions. In the university sector, the two national universities (Qatar University and Education City's Hamad Bin Khalifa University) recently opened several new Ph.D. programs and created new funding and mentoring programs to encourage Qatari citizens to pursue post-secondary higher education, primarily in the natural sciences.

Building indigenous capacity is a significantly more difficult and long-term goal than attracting building a research infrastructure to attract global science. Apprenticeship in the sciences is a long process, and it may take a decade or more before returns on these investments become evident, if indeed they succeed. In the mean time, R&D decision makers must balance the effort to develop local capacity with the unavoidable need for foreign scientific labor and the inescapable reality that science is an inherently collaborative and global enterprise.

Figure 11: Comparison of Articles Authored by Only a Qatar-Based Institution vs. Articles Authored in Collaboration with Non-Qatar-Based Institutions



5. Potential Beneficiaries

Among the many potential beneficiaries of the project research results are the scientific community of science researchers, the universities and research institutes and other organizations devoted to peer-reviewed science, and policymakers not only in the partner countries, but indeed in all countries as they invest in R&D. Funders and foundations of scientific activities will profit from the discussion of trends and patterns in productivity depending on the structures and investments in R&D.

Beneficiaries include the higher education and science research communities, scientists involved in bibliometrics, and institutionalists who chart the massive expansion of science producation and collaboration across the globe. The rise of evaluation and audit as tools to steer innovation relies on processes of comparison and peer review that are explicitly linked in the

SPHERE project as we illuminate issues of quantity and quality in publishing scientific discoveries.

Furthermore, journals editors and publishing companies will be able to utilize our findings in their everyday work as they better understand the field in which they are active. Most broadly, all authors of papers in STEM disciplines may benefit from seeing the publication patterns in their field, their language, their country and, where available, their organization.

6. Recommendations

- Higher education, and in particular universities, is key to the future development of science capacity in all countries examined. Science policy should be conceived, planned and implemented in conjunction with higher education policy.
- Research should not focus solely on the United States. Even among the other top producers—including China, Germany, Japan, France, Canada, Italy, India, and Spain—there is limited research. Furthermore, many other countries that are developing their research capacity and these patterns should be the subject of future research, for example the cases of Qatar and Luxembourg first analyzed by the SPHERE project.
- Especially given the rise of international collaborations, empirical studies should be—indeed must be—comparative to capture the cooperative ventures and exchange of ideas necessary for innovative research and scientific discoveries.
- The SPHERE project members invested tremendous efforts to recode especially the historical data (1900–1975), but limits of time and access to archived journals limited the geographic and linguistic scope of these cutting-edge historical analyses.

- The SPHERE project members conducted preliminary comparisons of the Thomson Reuters and Elsevier Scopus databases to ensure the reliability of the analyses, but these comparisons should continue to be done systematically to ensure reliable trend analysis.
- Research should extend horizontally beyond SCIE to include all the disciplines of scientific inquiry and vertically within specific disciplines (and journals) to better understand publication patterns and trends.
- Future research should not focus solely on STEM+ fields.
- Future research should focus on new data collection methods to improve measurement of science produced in other languages (i.e., non-English publications).

7. Conclusions

- "Big science" has been transformed by unprecedented production worldwide since the 1950s; we can now speak of "mega-global science." Exponential growth in article production reflects the increased importance of science worldwide.
- Despite major wars and global economic crises, there has been no decline or slowing of exponential growth in science production up to today.
- Competition for scientific impact is global. All regions, in particular the dominant scientific regions (North America, Europe, East Asia) are in direct competition. Simultaneously with this rising competition is vastly increased collaboration across national, linguistic, and organizational boundaries. Information technology and travel have extended the global reach and relevance of individual scholars and facilitated global research projects across the disciplines.
- The US is suffering a relative decline in scientific productivity, as especially Asian and European countries invest heavily in their national higher education and research

capacity. Newer competitors like Qatar and Luxembourg attempt via massive investment in university structures to play relevant roles in mega-global science.

- The worldwide scientific enterprise requires the sites of research capacity-building to fit into global production flows.
- Simultaneously with competition for scientific impact, the pursuit of cutting-edge knowledge production relies on building international and intercultural scholarly networks (and at all levels, not simply established members of science academies).
- Research and development requires investment not only in a cutting-edge campus or laboratories, but also in the networks, connections and exchanges that facilitate discoveries.

8. Bibliography

Adams, J. D. 2009. *Is the U.S. losing its preeminence in higher education?* (Working Paper No. 15233). Retrieved from http: www.nber.org/papers/w15233

Adams, J. D., Black, G. C., Clemmons, J. R., & Stephan, P. E. 2005. "Scientific teams and institutional collaborations: Evidence from US universities, 1981–1999." *Research Policy* 34(3):259-285.

Adams, Jonathan. 2013. "The fourth age of research." *Nature* 497:557-560.

Aghion, P., Dewatripont, M., and Stein, J. C. 2008. "Academic freedom, private-sector focus, and the process of innovation." *The RAND Journal of Economics* 39(3):617-635.

Allison, P. D. and Stewart, J. A. 1974. "Productivity Differences among Scientists: Evidence for Accumulative Advantage." *American Sociological Review* 39(4):596-606.

Allison, P. D. 1980. "Inequality and Scientific Productivity." *Social Studies of Science* 10(2): 163-179.

Allison, P. D., Long, J. S. and Krauze, T. K. 1982. "Cumulative Advantage and Inequality in Science." *American Sociological Review* 47(5):615-625.

Andrews, F.M. 1979. *Scientific Productivity: The Effectiveness of Research Groups in Six Countries*. Cambridge: Cambridge University Press.

Bailey, T.G. 1992. “Faculty Research Productivity.” Paper presented at the ASHE Annual Meeting, Minneapolis, MN.

Baker, D. 2008. “Privatization, Mass Higher Education, and the Super Research University: Symbiotic or Zero-sum Trends?” *Die Hochschule: Journal für Wissenschaft und Bildung (German Journal on Higher Education)* 2:36-52.

Baker, D. P. 2014. *The Schooled Society: The Educational Ttransformation of Global Culture.* Stanford, CA: Stanford University Press.

Ball, Rafael, and Tunger, D. 2005. *Bibliometrische Analysen – Daten, Fakten und Methoden. Grundwissen Bibliometrie für Wissenschaftler, Wissenschaftsmanager, Forschungseinrichtungen und Hochschulen*. *Schriften des Forschungszentrums Jülich. Band* 12. Jülich: Forschungszentrum Jülich.

Bayer, A. and Dutton, J.E. 1977. “Career age and research professional activities of academic scientists.” *Journal of Higher Education* 48:259–282.

Ben-David, J. 1984. *The Scientist’s Role in Society*. Chicago: The University of Chicago Press.

Blackburn, R.T., Behymer, C.E. and Hall, D.E. 1978. “Research note: Correlates of faculty publications.” *Sociology of Education* 51(April):132–141.

Bornmann, L., and Mutz, R. 2015. “Growth rates of modern science: A bibliometric analysis.” *Journal of the Association for Information Science and Technology.*

Bornmann, L., Wagner, C., and Leydesdorff, L. 2015. “BRICS countries and scientific excellence: A bibliometric analysis of most frequently-cited papers.” *Journal of the Association for Information Science and Technology* 66(7):1507-1513.

Bornmann, L., Mutz, R., Neuhaus, C., and Daniel, H.D. 2008. “Use of Citation Counts for Research Evaluation: Standards of Good Practice for Analyzing Bibliometric Data and Presenting and Interpreting Results.” *Ethics in Science and Environmental Politics* 8:93-102.

BQDoha staff. 2013. “Qatar Sets Aside Record QR 210 bn for public spending.” BQDoha Magazine, April. Retrieved July 27, 2015 (http://www.bqdoha.com/2013/04/qatar-sets-aside-record-qr-210-bn-for-public-spending_a).

Bradford, Samuel C. 1934. “Sources of information on specific subjects.” *Engineering: An Illustrated Weekly Journal* 137(3550):85-86.

Brookes, B.C.1990. “Biblio-, Sciento-, Infor-metrics??? What are we talking about?” Pp. 31-43 in *Informetrics 89/90. Selection of Papers Submitted for the Second International Conference on Bibliometrics, Scientometrics and* Informetrics, edited by L. Egghe and R. Rousseau. Amsterdam: Elsevier.

Cameron, S.W. and Blackburn, R.T. 1981. “Sponsorship and academic career success.” *Journal of Higher Education* 52(4):369–377.

Chen, Dehu. 1999. “The reform trend of Taiwan higher education.” *Education Research Information* 7(3):1-12

Clemente, F. 1973. “Early career determinants of research productivity.” *American Journal of Sociology* 79(2):409–419.

Cole, Francis J., and Eales, Nellie B. 1917. “The History of Comparative Anatomy.” *Science Progress* 11:578-596.

Cole, J. R. And Cole, S. 1973. *Social Stratification in Science.* Chicago: The University of Chicago Press.

Cole, S. and Phelan, T. J. 1999. “The Scientific Productivity of Nations.” Minerva 37: 1-23.

Crist, J. T. 2015. “Innovation in a Small State: Qatar and the IBC Cluster Model of Higher Education.” *The Muslim World* 105(1):93-115.

Cui, L. C. 2000. “A study on the S&T policies of the CPC since 1949.” Ph.D. dissertation, The Party School of the Central Committee of C.P.C.. Retrieved from https://vpn.ccnu.edu.cn/kns/brief/,DanaInfo=epub.cnki.net+default_result.aspx [in Chinese].

de Solla Price, D. J. 1961. *Science since Babylon*. New Haven, CT: Yale University Press.

de Solla Price, D. J. 1963. *Little science, big science, and beyond*. New York: Columbia University Press.

De Solla Price, D. J. 1974. *Little Science, Big Science*. Von der Studierstube zur Großforschung. Frankfurt am Main: Suhrkamp. (deutsche Übersetzung)

Dobbs, R., Remes, J., Manyika, J., Roxburgh, C., Smit, S., and Schaer, F. 2012. *Urban world: Cities and the rise of the consuming class.* McKinsey Global Institute. Retrieved from http://www.mckinsey.com/insights/urbanization/urban_world_cities_and_the_rise_of_the_consuming_class

Dobrov, Gennadij, M. 1966. Nauka o Nauke. Kiew: Naukova Dumka. (Russian Edition).

Dong, B. L., Dan, Z. B., and Chen, Q. 2007. *The modern history of higher education in China*. Wuhan: Huazhong University of Science and Technology Press [in Chinese].

Dong, Baocheng. 1997. *Education law and academic freedom*. Yuedan Press.

Drori, G. 2000. “Science education and economic development: Trends, relationships, and research agenda.” *Studies in Science Education* 35:27-57.

Drori, G., Meyer, J. W., Ramirez, F. O., and Schofer, E., eds. 2003. *Science in the Modern World Polity: Institutionalization and Globalization*. Stanford, CA: Stanford University Press.

Eiduson, B. T. 1962. *Scientists: Their Psychological World*. New York: Basic Books.

Etzkowitz, H., and Leydesdorff, L. 2000. “The dynamics of innovation: from National Systems and “Mode 2” to a Triple Helix of university–industry–government relations.” *Research policy*, 29(2):109-123.

Etzkowitz, H., Webster, A., Gebhardt, C., and Terra, B. R. C. 2000. “The future of the university and the university of the future: evolution of ivory tower to entrepreneurial paradigm.” *Research policy* 29(2):313-330.

Gantman, E. R. 2012. “Economic, linguistic, and political factors in the scientific productivity of countries.” *Scientometrics* 93(3):967-985.

Gao, L., and Zhao, W. H. 2010. “A comparative study on the R&D expenditure and entrepreneurship between Chinese and American research universities.” *China Higher Education Research* 5:39-42 [in Chinese].

Garfield, Eugene. 1955. Citation Indexes for Science. *Science* 122:108.

Garfield, Eugene. 1964. “Science Citation Index–A New Dimension in Indexing.” Science 144: 649-654.

Geiger, R. L. 1986. *To advance knowledge: The growth of American research universities, 1900-1940*. New York: Oxford University Press.

Geiger, R., and Sá, C. M. 2008. *Tapping the riches of science: Universities and the promise of economic growth*. Cambridge, MA: Harvard University Press.

Gibbons, M., Limoges, C., Nowotny, H., Schwartzman, S., Scott, P., and Trow, M. 1994. *The new production of knowledge: The dynamics of science and research in contemporary societies*. Thousand Oaks, CA: Sage.

Glänzel, Wolfgang. 2003. “Bibliometrics as a research field: A course on theory and application of bibliometric indicators.” Course Handout. Retrieved from http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.97.5311&rep=rep1&type=pdf, last accessed: 20150115

Glänzel, Wolfgang (ohne Jahr), n.d. *A Concise Introduction to Bibliometrics & its History*. Retrieved from https://www.ecoom.be/en/research/bibliometrics, last accessed 20150115.

Glänzel, Wolfgang, Schöpflin, Urs. 1994. “Little Scientometrics, big scientometrics–and beyond?” *Scientometrics* 30(2-3):375-384.

Godin, B., and Gingras, Y. 2000. “The place of universities in the system of knowledge production.” *Research policy* 29(2):273-278.

Goldin, C. D., and Katz, L. F. 2009. *The Race between Education and Technology*. Cambridge: Harvard University Press.

Graf, Lukas, Justin J.W. Powell, Johann Fortwengel, and Nadine Bernhard. 2014. *Dual Study Programmes in Global Context: Internationalisation in Germany and Transfer to Brazil, France, Qatar, Mexico and the US.* Bonn: German Academic Exchange Service (DAAD).

Gross, P. L. K.; Gross, E. 1927. “College Libraries and Chemical Education.” *Science* 66: 385-389.

Havemann, Frank. 2009. *Einführung in die Bibliometrie*. Berlin: Gesellschaft für Wissenschaftsforschung.

Havergal, Chris. 2015. “MENA Snapshot Puts Texas A&M at Qatar in Top Spot.” Times Higher Education, January. Retrieved July 28, 2015 (https://www.timeshighereducation.co.uk/news/mena-snapshot-puts-texas-am-at-qatar-in-top-spot/2018230.article).

Hayhoe, R. .1996. *China’s universities 1895-1995: A century of cultural conflict*. New York: Garland Pub.

Hessels, L. K., and Van Lente, H. 2008. “Re-thinking new knowledge production: A literature review and a research agenda.” *Research policy* 37(4):740-760.

Hulme, E. Wyndham. 1923. *Statistical bibliography in relation to the growth of modern civilization*. London: Butler & Tanner, Grafton & Co.

Ida, T., and Fukuzawa, N. 2013. “Effects of Large-Scale Research Funding Programs: A Japanese Case Study.” *Scientometrics* 94:1253-1273.

Jovanovic, Milos. 2012. “Eine kleine Frühgeschichte der Bibliometrie.” *Information, Wissenschaft & Praxis* 63(2):71-80.

King, D. A. 2004. “The scientific impact of nations.” *Nature* 430:311-316.

Kobayashi, S. 2005. 'Chishikino Sozoukyoten toshiteno Kokuritsu Daigaku ', The Japan Association of National Universities, ed., "21seiki Nihon to Kokuritsu Daigaku no Yakuwari", JANU Quarterly Report, The Japan Association of National Universities, pp.1-21.(in Japanese).

Li, H. F. 2011. “The experience of Chinese Academy of Sciences in talents building.” *China’s Talents* 6:30-32.

Liao, W. 2010. “A comparative study on the R&D input of China and OECD countries.” *Special Zone Economy* 8:107-109 [in Chinese].

Lightfield, E. T. 1971. “Output and Recognition of Sociologists.” *The American Sociologist* 6(2): 128-133.

Long, J. S. 1977. *Productivity and Position in the Early Academic Career*. Ithaca: Cornell University.

Lotka, Alfred J. 1926. “The frequency distribution of scientific productivity.” *Journal of the Washington Academy of Sciences* 16(12):317-323.

Maul, Stefan M. 2006. *Das Gilgamesch-Epos*. München: C. H. Beck.

May, R. M. 1997. ”The Scientific Wealth of Nations.“ *Science* 275(5301):793-796.

McClellan, Jason E. 2003. “Specialist Control: the Publications Committee of the Académie Royal des Sciences (Paris) 1700-1793.” *Transactions of the American Philosophical Society* 93. Philadelphia: American Philosophical Society.

Meo, S. A., Al Masri, A. A., Usmani, A. M., Memon, A. N., and Zaidi, S. Z. 2013. “Impact of GDP, spending on R&D, number of universities and scientific journals on research publications among Asian countries.” *PLOS One* 8(10):e66449.

Meo, S. A., Usmani, A. M., Vohra, M. S., and Bukhari, I. A. 2013. “Impact of GDP, spending on R&D, number of universities and scientific journals on research publications in pharmacological sciences in Middle East.” *European Review of Medical and Pharmacological Sciences* 17(20): 2697-2705.

Merton, R. K. 1970. “Science, Technology and Society in Seventeenth Century England.” New York: Howard Fertig Press.

Merton, R. K. 1988. “The Matthew Effect in Science, II: Cumulative Advantage and the Symbolism of Intellectual Property.” *Isis* 79(4):606-623

Merton, R. K. 1968. “The Matthew Effect in Science.” *Science* 159(3810):56-63.

Merton, R. K. 1942. “The Normative Structure of Science.” *Science*.

Meyer, J. W. 1977. “The effects of education as an institution.” *American Journal of Sociology*, 83(1):55-77.

Meyer, J. W., Ramirez, F. O., Frank, D. J., and Schofer, E. 2008. “Higher Education as an Institution.” Pp. 187-221 in *The sociology of higher education: Contributions and their* contexts, edited by P. Gumport. Baltimore, MD: The Johns Hopkins University Press.

Ministry of Education.1996. “The Management Regulation of School Fund System in National University.

Ministry of Education, Taiwan. 2013. *Digest of Educational Statistics*. Retrieved February 16, 2013.

Ministry of Education, Taiwan. 2014. *Digest of Education Statistics*. Retrieved from http://www.edu.tw/pages/detail.aspx?Node=4075&Page=20046&Index=5&WID=31d75a44-efff-4c44-a075-15a9eb7aecdf

Mohrman, K., W. Ma, and D. Baker. 2008. “The research university in transition: The emerging global model.” *Higher Education Policy* 21: 5–27.

Nalimov, Vasily; Mulchenko, Z.M. 1969. Naukometriya. Nauka. (Zitiert nach: Juvanovic 2012).

National Academy for Education Research. 2012. *The White Paper of Talent Cultivation*. Retrieved January15, 2013.

National Science Council. 2013. *Digest of Scientific Indicators*. Retrieved February 18, 2013, from https://nscnt12.nsc.gov.tw/WAS2/main/AsMain.aspx

National Taiwan University. 2013a. *The Organization Regulation of National Taiwan University*. Retrieved February17, 2013, from http://host.cc.ntu.edu.tw/sec/all_law/1/1-04.html

National Taiwan University. 2013b. *The Report of Financial Structure*. Retrieved March 12, 2013, from http://www.ntu.edu.tw/about/statistics.htm

OECD. 2013. *Science, Technology and Industry Scorecard*. Retrieved from http://www.oecd-ilibrary.org/science-and-technology/oecd-science-technology-and-industry-scoreboard-2013_sti_scoreboard-2013-en

O’Neill, J. 2001. *Building better global economic BRICs*. Global Economics Paper 66. New York: Goldman-Sachs

Otlet, Paul. 1934. Traité de Documentation. Brüssel.

Over, R. 1982. “Does research productivity decline with age?” *Higher Education* 11(5):511–520.

Pelz, D.C., and Andrews, F.M. 1966. “Scientists in Organizations: Productive Climates for Research and Development.” New York: Wiley.

People’s Network. 2006, December 31. *Common Program of the Chinese People’s Consultative Conference*. Retrieved from http://www.hnredstar.gov.cn/yueyang123/djgz/dj_zywx/t20061230_84917.html [in Chinese]

Pfeffer, J., and Salancik, G. R. 1978. *The External Control of Organizations*. New York: Harper & Row.

Powell, Justin J.W. 2014a. “University Roots and Branches Between ‘Glocalization’ and ‘Mondialisation’: Qatar’s (Inter)National Universities.” *International Perspectives on Education and Society* 24:253-276.

Powell, Justin J.W. 2014b. “International National Universities: Migration and Mobility in Luxembourg and Qatar.” Pp. 119-134 in *Internationalisation of Higher Education and Global Mobility,* Bernhard Streitwieser, ed. Oxford: Symposium Books.

Powell, Justin J.W. 2015. “وقطر لوكسمبورج فى (التنقليه) والتنقل الهجرة : الدولية الوطنية الجامعات” Arabic translation of Powell 2014b. DOI: 10.13140/RG.2.1.5124.4641, available at http://hdl.handle.net/10993/21566

Price, D. 1963. *Little Science, Big Science…and Beyond*. New York: Columbia University Press.

Pritchard, Alan. 1969. "Statistical Bibliography or Bibliometrics?" *Journal of Documentation* 25(4):348-349.

Reisz, R. D. and Stock, M. 2007. "Theorie der Weltgesellschaft und statistische Modelle im soziologischen Neo-institutionalismus," *Zeitschrift für Soziologie* 36(2):82-99.

Reskin, B. F. 1977. "Scientific Productivity and the Reward Structure of Science." *American Sociological Review* 42(3):491-504.

Romer, P. M. 1986. "Increasing returns and long-run growth." *The Journal of Political Economy* 94(5):1002-1037.

Saka, A., and Kuwahara, T. 2012. *Benchmarking Research and Development Capacity of Japanese Universities 2011: Improving universities research activities by identifying characteristics and strength of each university*. National Institute of Science and Technology Policy (NISTEP), MEXT [in Japanese].

Saka, A., and Kuwahara, T. 2012. *Benchmarking Scientific Research 2011: Bibliometric analysis on dynamic alteration of research activity in the world and Japan*. National Institute of Science and Technology Policy (NISTEP), MEXT [in Japanese].

Sampson, G. 1985. *Writing Systems*. Stanford: Stanford University Press.

Schofer, E. 2004. "Cross-national differences in the expansion of science, 1970–1990." *Social Forces* 83(1):215-248.

Schofer, E., and Meyer, J. W. 2005. "The worldwide expansion of higher education in the twentieth century." *American Sociological Review* 70(6):898-920.

Sciences. *ScienceNet*. Retrieved from http://talent.sciencenet.cn/index.php?s=Info/index/id/8598 [in Chinese]

Shima, K. 2012. "Changes in national university finances in Japan: After incorporation." *Japanese Journal of Higher Education Research* 15:49-70 [in Japanese].

Shima, K. 2011. 'Secchi syutaibetsu, Daigaku ruikeibetsu nimita kenkyukino', R.I.H.E. (Ed.), "Kokuritsu Daigaku no Kino ni kansuru Jissyoteki Kenkyu." Senryakuteki Kenkyu Project 3:33-38 [in Japanese].

Shockley, W. 1957. "On the statistics of individual variations of productivity in research laboratories." *Proceedings of the Institute of Radio Engineers* 45 (March).

Slaughter, S., and Leslie, L. 1997. *Academic Capitalism: Politics, Policies and the Entrepreneurial University*. Baltimore: Johns Hopkins University Press.

Solow, R. M. 1957. "Technical change and the aggregate production function." *The Review of Economics and Statistics* 39(3):312-320.

Solt, F. 2009. "Standardizing the World Income Inequality Database." *Social Science Quarterly*

90(2):231-42.

Song, M. M., and Tai, H. H. 2007. “Taiwan's responses to globalisation: internationalisation and questing for world class universities.” *Asia Pacific Journal of Education* 27(3):323-340.

Statistics Bureau. 2012. *Report of Economic Development*. Retrieved January 5, 2013, from http://www.stat.gov.tw/mp.asp?mp=4

Taylor, C. W. and Barron, F. 1963. *Scientific Creativity: Its Recognition and Development*. New York: Wiley.

Teodorescu, D. 2000. “Correlates of faculty publication productivity: A cross-national analysis.” *Higher Education*, *39*(2):201-222.

The Recruitment Program of Global Experts. 2008, December. Retrieved from http://www.1000plan.org/qrjh/section/2?m=rcrd [in Chinese]

The State Council of China. (1995). *The Decision on Expediting Progress in Science and Technology*. Beijing: The State Council of China.

Tsinghua University. 2013, September 27. *Research cooperation*. Retrieved from http://www.tsinghua.edu.cn/ publish/then/5990/index.html

UK Royal Society. 2011. *Knowledge, networks, and nations: Global scientific collaborations in the 21century*. London: Author.

UNDP. 2010. *The Real Wealth of Nations: Pathways to Human Development*. Human Development Report.

UNESCO Institute for Statistics. 2010. *Measuring R&D: Challenges Faced by Developing Countries*. Technical Paper No.5. Montreal: UNESCO Institute for Statistics. Retrieved from http://www.uis.unesco.org/Pages/default.aspx

U.S. Patent and Trademark Office. 2013. *Patenting By Geographic Region (State and Country).* Retrieved from http://www.uspto.gov/web/offices/ac/ido/oeip/taf/stcasg/twx_stcorg.htm

Wang, J., and Levitt, J. M. 2012. “The contribution to highly cited articles by authors from BRIC countries.” *Proceedings of 17th International Conference on Science and Technology Indicators*. Montreal: Science-Metrixd and OST.

White, Howard D., and McCain, Katherine W. 1989. “Bibliometrics.” *Annual Review of Information Science and Technology* 24:119-186.

Wissenschaftsrat. 2004a. Empfehlungen zu Rankings im Wissenschaftssystem Teil 1: Forschung. Drs. 6285-04. Hamburg.

Wissenschaftsrat. 2004b. Standortübergreifende Stellungnahme zur Weiterentwicklung der Universitätsmedizin in Baden-Württemberg. Drs. 6196-04. Berlin.

Wu, L. H., Peng, Y. Y., and Peng, X. Y. 2006. “Comparative study on the devotions of the R&D expenditures at home and abroad based on the three R&D main bodies and the three R&D

activities." *Scientific Management Research* 24(5):101-116 [in Chinese].

Wu, W. H. 1997. "A historical study of Chinese scientific and cultural policies." *Scientific Management Research* 15(5):16-20 [in Chinese].

Xu, Nanhao. 2002. *The History of Taiwan Education*. National Taiwan Normal University Press.

Yang, C. G. 2009, September 28. "The national strategy of establishing world-class universities." *China Education Daily*. Retrieved from http://www.jyb.cn/high/gjsd/200909/t20090928_313808.html [in Chinese].

Zhang, L., J.J.W. Powell, and D.P. Baker. 2015. "Exponential Growth and the Shifting Global Center of Gravity of Science Production, 1900–2011." *Change: The Magazine of Higher Learning* 47(4): 46-49.

Zhao, L. J. 2013, September. Talk in the conference of The Recruitment Program of Global Experts. Retrieved from http://www.1000plan.org/qrjh/article/40679 [in Chinese]

Zhao, Y. H. 2009, October 31. "Sixty years of Chinese Academy of Sciences." *Renmin Daily*. Retrieved from http://www.gov.cn/jrzg/2009-10/31/content_1453257.htm [in Chinese]

Zhen, Q. L. 2013, September 24. The Hundred Talents Program of the Chinese Academy of Sciences.

Zheng, Liling. 2001. "The Development of Imperial Taipei University during the Period of Japan Occupation." Ph.D. Dissertation, Department of History, National Taiwan University.

Zipf, George K. 1935. *The Psycho-Biology of Language: An Introduction to Dynamic Biology*. Cambridge: MIT Press.

Zipf, George K. 1949. *Human Behavior and the Principle of Least Effort: An Introduction to Human Ecology*. Boston: Addison-Wesley Press.

9. Nomenclatures

Not applicable

10. Appendices

Not applicable