The Century of Science

Introduction: The Worldwide Triumph of the Research University and Globalizing Science

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INTRODUCTION: THE WORLDWIDE TRIUMPH OF THE RESEARCH UNIVERSITY AND GLOBALIZING SCIENCE

Justin J. W. Powell, Frank Fernandez, John T. Crist, Jennifer Dusdal, Liang Zhang and David P. Baker

ABSTRACT

Purpose – *This chapter provides an overview of the findings and chapters of a thematic volume in the* International Perspectives on Education and Society *(IPES) series. It describes the common dataset and methods used by an international research team.*

Design/methodology/approach – *The chapter synthesizes the results of a series of country-level case studies and cross-national and regional comparisons on the growth of scientific research from 1900 until 2011. Additionally, the chapter provides a quantitative analysis of global trends in scientific, peer-reviewed publishing over the same period.*

Findings – *The introduction identifies common themes that emerged across the case studies examined in-depth during the multi-year research project Science Productivity, Higher Education, Research and Development and the Knowledge Society (SPHERE). First, universities have long been and are increasingly the primary organizations in science production around the globe. Second, the chapters describe in-country and cross-country patterns of*

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competition and collaboration in scientific publications. Third, the chapters describe the national policy environments and institutionalized organizational forms that foster scientific research.

Originality/value – *The introduction reviews selected findings and limitations of previous bibliometric studies and explains that the chapters in the volume address these limitations by applying neo-institutional theoretical frameworks to analyze bibliometric data over an extensive period.*

Keywords: Science production; research policy; research university; sociology of science; bibliometrics; Science Citation Index Expanded (SCIE)

SETTING THE GLOBAL STAGE

This volume of *International Perspectives on Education and Society* presents results of a multi-year, cross-national investigation of the influence of higher education development, specifically the research university, and science capacity-building on scientific knowledge production. 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, from 1900 to 2011. It analyzes countries of different size and histories of university institutionalization and scientific production. The global comparative project called "Science Productivity, Higher Education, Research and Development and the Knowledge Society" (SPHERE) produced a comprehensive longitudinal and worldwide dataset of scientific journal publications on science, technology, engineering, and mathematics, plus health (hereafter STEM+) cataloged in the Science Citation Index Expanded (SCIE), customized and acquired especially for this project from Thomson Reuters' (now Clarivate Analytics) Web of Science (formerly ISI Web of Knowledge).

Comparing dynamics in the oldest and largest research environments with trends in fast-developing knowledge economies, the SPHERE project contrasts institutionalization pathways and scientific productivity in selected countries in Europe, North America, East Asia, and the Middle East. While non-university research institutes continue to generate new science, the project shows that over the past century it has been research universities, plus a growing number of less research-intensive universities, leading the way in the expansion of science. So much so that worldwide annual scientific publications authored by at least one university-based scientist grew exponentially from about one half in the 1960s to currently 85% of all STEM+ papers. The project's overall results demonstrate that, despite numerous wars, regime changes, and global economic crises, there has been no lasting decline or slowing of the growth of scientific research – up to today. In fact, "big science" was itself transformed by unprecedented heightened production, beginning just after mid-century. At the same time, the project's institutional analyses show interesting similarities and differences in national models, of varying global influence, that facilitated the ongoing development of research universities and non-university institutes in contrasting systems – some more reliant on universities and others with research capacity distributed across multiple institutional sources of science and organizational forms. Our case studies include China, France, Germany, Japan, Qatar, South Korea, Taiwan, the United Kingdom, and the United States. These analyses have been conducted and written by scholars either working in the countries analyzed or heralding from those cultures, facilitating explanation of long-term cross-national trajectories in scientific productivity across the world centers of higher education expansion and scientific production.

The chapters assembled here respond to mid- and late-20th century scholars, many of whom predicted the decline of "big science," with which World War II was won (Kleinman, 1995), and later scholars who claimed that universities would not keep pace with private industry in producing new scientific knowledge. Scientometricians were among the first to mark the advent of "big science" in the 1960s, yet they also predicted that over the next few decades, the pure exponential growth of science publications would slow down significantly due to saturation, reducing the global rise in science production (de Solla Price, 1963). Yet, they failed to anticipate a crucial rising trend, and what supported it. Starting in the 1960s, the world's capacity to generate new scientific knowledge went to a new level – "mega-science" (Elzinga, 2012). As shown in Fig. 1, STEM+ publications grew at an exponential annual rate of 3.5%, so that now well over one million new research articles are published every year in a plethora of peer-reviewed scientific journals. At the same time, what was once mostly done by scientists in European and North American universities has become a global undertaking. The United States' past predominance of science is increasingly shared with other countries. For example, although in 2011 the United States produced almost 282,000 publications (26% of total STEM+ publications had at least one U.S.-based author) compared to China's 152,000 publications (14%). The world's center of gravity of science production is moving away from North America, returning toward Europe, with its very strong science-producing countries, also due to the rise of Asian production (Zhang, Powell, & Baker, 2015). And, as noted above and detailed in the following chapters, increasingly the world's new science is rooted in the exceptional expansion of higher education and the on-going development of research universities.

The SPHERE project coded and analyzed over 20 million records from the SCIE dataset to show that the number of STEM+ papers published in scientific journals over the 20th century grew extraordinarily rapidly (Zhang et al., 2015). Starting from slightly above 9,500 in 1900, the annual number of new publications grew to about 50,000 in 1960, nearly doubling again by 1965. This early

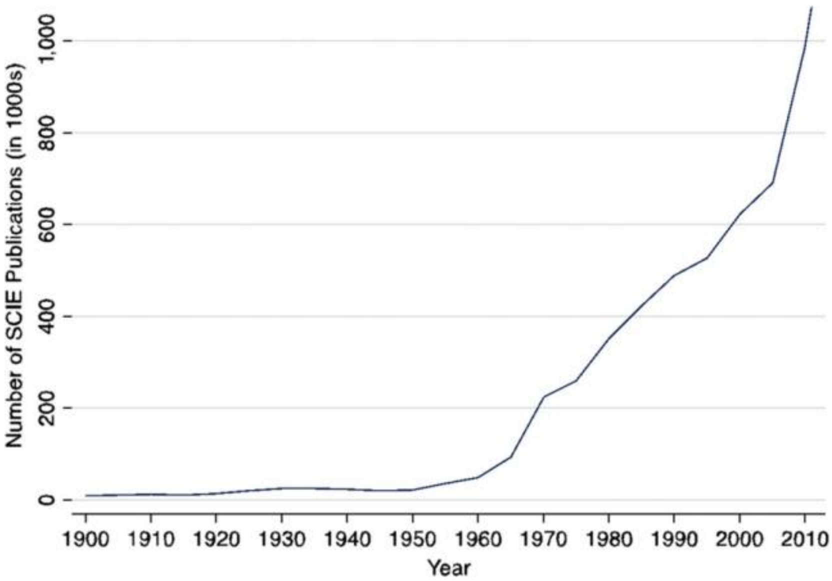

Fig. 1. Exponential Growth in STEM+ Articles Published Worldwide, 1900–2011. *Source*: SPHERE project database of SCIE publications (Thomson Reuters' Web of Science).

trend, often referred to as "big science," was then transformed into what we will refer here to as "global mega-science": pure exponential growth reflecting extraordinary and continued growth in peer-reviewed publications between 1980 and 2010, leading to over half a million SCIE publications in 1995 and doubling again by the year 2011 (Fig. 1).

Next to the massive rise in the absolute number of published STEM+ papers, especially since 1960, another important phenomenon was the globalization of science. The numbers of countries contributing to this extraordinary total output also grew impressively. While in 1900 only around two dozen countries and territories participated in the production of STEM+ papers, by 1950 this number increased to three dozen. By 1980, this number more than quadrupled again, and by the turn of the century around 200 countries and territories had produced science (Mihai & Reisz, 2017). The average number of papers produced by a country has also increased since 1900, from 416 to 1,189 in 1950, and 3,779 in 2000. By 2010, within just one decade, the average number, 6,262, had risen again by 65%. These illustrate the growth, but mask an accompanying global bimodal process. Early in the century, scientists in a small number of countries produced most STEM+ papers, then by expanding their capacity are annually publishing thousands by the end of the century. But also over the century, scientists working in ever more countries begin to produce significant amounts of papers, and by the end of the century even smaller, and in some ways unlikely, countries such as Luxembourg (Powell & Dusdal, 2016) and Qatar (Crist, 2017), are participating in global mega-science.

It is generally recognized that recent and unprecedented science production derives from the prior expansion of every level of education, and the resulting greater production of those capable and willing to conduct advanced research. It also results from the long-term evolution of publication outlets, with some journals publishing the most significant scientific results for decades, and the rising number of journals and the ongoing specialization of science. There has been a significant rise in the volume of SCIE publications from scientists in a growing number of nations – in other words, the globalization of science (The Royal Society, 2011). The 10 countries that produced the most SCIE publications (in 1,000s) in 2011 were the United States (282,000), China (153,000), Germany (80,000), the United Kingdom (74,000), Japan (69,000), France (57,000), Canada (46,000), Italy (46,000), India (43,000), and Spain (41,000). Thus, currently, Europe is the region with the most countries contributing largely to global scientific production, based on ancient universities embedded in high-capacity, publically funded science systems.

Thus, not only were early arguments about the decline of the research university wrong, but again in the 1990s leading scholars in science studies argued incorrectly that other organizational forms would become central. Although research universities have, for decades and indeed centuries, been key sites of knowledge production (Geiger, 1986; Rüegg, 2004, 2011), many contemporary scholars questioned the role of universities in knowledge production and innovation – or even began to predict that the locus of scientific research would shift away from largely state-funded higher education to a variety of other organizational forms (see Hessels & van Lente, 2008; van Rooij, 2014 for reviews). Indeed, the era since the Great Recession has challenged the public funding of higher education and research, again leading to questions about the economic and social contributions of universities in many countries. Whereas the two dominant Anglophone science-producing countries of the United States and the United Kingdom have seen retrenchment in public investments in higher education, state funding remains central in most other countries analyzed in this volume, with the exception of South Korea.

Today, higher education, particularly research universities, and science systems continue to experience transformation. Not least this is due to active governance or retrenchment, the definition of strategic goals and elaborate research evaluation systems, and performance-based funding of university researchers (Hicks, 2012). The orientation to scientific "excellence" or "quality" and "relevance" or "impact" worldwide has led to innumerable initiatives to advance these often competing, yet sometimes complementary goals. While numerous approaches try to explain how these changes have developed, scholars continue to contest their sources. Private enterprises play different roles in various types of scientific production, often emphasizing industrial applications and patents to secure commercialization of scientific discoveries. Yet increasingly inter-sectoral collaboration, academic engagement, and career mobility as well as hybrid organizational forms that tie universities and industry together facilitate diverse forms of scientific communication and output (Dietz & Bozeman, 2005; Perkmann et al., 2013).

Instead of examining patents as a measurable form of scientific productivity or output deriving from R&D investments (Griliches, 1984), the SPHERE project focuses on fundamental or "basic" research as measured in peer-reviewed articles in leading journals, considered the "gold standard" in the academic world. Here, we pay more attention to the absolute and relative growth of academic research and multidisciplinary and international collaborations than to the citations accruing to any single article. Unlike much of the existing literature on the topic of scientific production, this volume of *International Perspectives on Education and Society* reports on new systematic estimates of the number of worldwide STEM+ science publications from 1900 to 2011, combined with in-depth historical case studies of research university and research institute development as well as higher education and research policy.

This remarkable productivity reflects two contrasting and simultaneous phenomena – rising competition across nations and universities at the macro and meso levels and globe-spanning collaboration among universities, research groups, and individual scientists at the meso and micro levels. These developments must be understood in the context of the global knowledge society, itself precipitated by three trends. First, the institutionalization of schooling and education at all levels and throughout the world (Baker, 2014; Drori & Krücken, 2009; Meyer, 1977). Second, the massive and continuing expansion of university enrollments around the world that has transformed science into an everyday activity everywhere (Meyer, Ramirez, Frank, & Schofer, 2008; Schofer & Meyer, 2005). And third, as new universities were founded around the world, and tertiary education became increasingly accessible as well as institutionally embedded, the *research university* became a global model for higher education and knowledge production and this strengthened research capacity worldwide (Baker, 2014). Higher education expansion led to new forms of knowledge and policymakers have increasingly identified and actively managed education and science as key sources of economic growth (Drori, 2000). We find increased scientization in global culture (Drori, Meyer, Ramirez, & Schofer, 2003), including especially information technologies, educational exchange and scientific mobility, and supranational governance also evident in the ongoing regional standardization of higher education systems (Powell, Bernhard, & Graf, 2012).

SPHERE was the first project of its kind to analyze factors behind cross-national trajectories of scientific knowledge across the entire last century, building on a neo-institutional theoretical approach and a comprehensive dataset, and to pair this with systematic historical quantitative cross-national comparisons to examine shifting national contributions to global science. Theoretically, we focus on the increased legitimacy of the university and other scientific organizations in pursuing educational and scientific activities and the institutional models that gained influence globally as diverse organizational forms grew within complex organizational fields. We compare different institutionalization pathways of complex higher education and science systems. Our cross-cultural project team, based in eight countries, created and analyzed a new, huge global dataset on research articles in "mainline" scientific journals – science, technology, engineering, mathematics, health and medical fields (STEM+) between 1900 and 2011. The resulting cross-national database provides indicators to assess the influence of higher education development and science capacity-building on scientific knowledge production. Conducting a series of case studies to examine how systems of higher education developed and nations' capacity for scientific research grew, the team relied on the knowledge of the assembled experts to assess the impact of the research university and expanding higher education on postindustrial societies in Europe, North America, East Asia, and the Middle East.

This volume's chapters contribute to this scientific aim as well as they may inform national and supranational policymakers seeking to enhance contributions to the global enterprise of higher education and science, especially as countries diverge in the relative contributions of public and private sources invested in these systems. The findings may support policy recommendations to meet the challenges of the global knowledge society. This introduction first connects the SPHERE project to existing literatures, then discusses in-depth the methodological approach and choices made in preparing the data for analysis, examines global trends longitudinally and comparatively across the selected countries, and introduces the country and comparative studies included in this volume.

EMBEDDING SPHERE IN SCIENTIFIC LITERATURE

As mentioned above, a key strand of literature relating to higher education and science discusses the different organizational forms that contribute to scientific production. Old and new institutionalists emphasize organizational forms and fields that structure complex institutional environments (Scott, 2015). From research universities and institutes to government agencies and military to industry as well as scientific academies, laboratories, and museums (among others), diverse organizational forms regularly utilize, produce, and distribute what, at that time, is considered scientific knowledge (on Germany, see Dusdal, 2017). The contributions, in their intellectual and physical forms, and their modes of distribution vary considerably over time, but for centuries, the university has been a key environment facilitating the construction, transmission, and advancement of knowledge, in the *lingua franca* of each era – more than ever in formalized written forms, such as the research monograph and article.

The Organization of Science Production: Research Universities at the Center

If tremendous diversity exists in the organizations producing science today, our analyses show that the very center of scientific productivity has become – and remains – the research university. 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 a research-producing institution, while universities took on ever more central roles in society (Etzkowitz & Leydesdorff, 2000). University researchers have tended to be more focused on long-term knowledge production that has led to the rise of new, multi- or interdisciplinary fields, such as molecular biology and biotechnology (Etzkowitz, Webster, Gebhardt, & Terra, 2000). Similarly, because universities are often involved in knowledge production in emerging areas of scientific inquiry, those research projects were often problematic or risky (Hall, Link, & Scott, 2003, p. 485): 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." In part, these sorts 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), relating to the need to make profits in the foreseeable future. Furthermore, the unique combination of elements of university missions, including intergenerational knowledge transfer and the certification of new knowledge via the granting of doctoral degrees, ensures continuous renewal and innovation. For example, in both France and Germany, despite crucial extra-university institutions that produce the most cutting-edge science, the universities retain centrality via their authority to train each new generation of scientists (Powell & Dusdal, 2017).

Although research universities have historically been the key sites of knowledge production (Riddle, 1989; Schofer, 2004), many scholars began to predict that the main locus of scientific research would shift away from higher education. In *The New Production of Knowledge*, Gibbons and colleagues postulated that there would be a shift from "Mode-1" to "Mode-2" production of knowledge, in which "universities, in particular, will comprise only a part, perhaps only a small part, of the knowledge producing sector" (Gibbons et al., 1994, p. 85; Nowotny, Scott, & Gibbons, 2001; see also Godin & Gingras, 2000). This work spawned a lively debate about the state of scientific research and the role of the research university in contemporary society – in fact, it became the most widely cited work on the topic (Hessels & van Lente, 2008). In contemporary science and society, the challenge remains to operationalize the principles of Mode-2 science for particular disciplines (but see Kropp & Blok, 2011 on sociology; Zapp & Powell, 2017 on education).

Scholars from various fields introduced competing models of the university's multidimensional role in science production, from "academic capitalism" (Slaughter & Leslie, 1997; Slaughter & Rhoades, 2009) to the "triple helix" of university/industry/government relationships (Leydesdorff & Etzkowitz, 1998; Leydesdorff & Meyer, 2006) and "post-academic science" (Ziman, 2000), to the "emerging global model" of the "Super Research University" (Baker, 2014; Mohrman, Ma, & Baker, 2008). Depicting various causes and consequences of such shifting constellations, such models all acknowledge that universities and science are embedded in a multidimensional space without one complete source of governance or funding. They identify changes in the ways in which universities produce knowledge in an increasingly interconnected, collaborative, globalized, and, despite policy rhetoric touting support for universities, resource-constrained world. As Delanty (2001) emphasizes, the contemporary transformation in communication fundamentally alters the modes of constructing and disseminating knowledge. However, some of these theories, in questioning the adaptability of the university as a highly institutionalized organizational form, have lacked empirical bases, leading to diverse normative judgments and contrasting implications for policymakers.

If policymakers think that universities contribute declining shares of science production, they will not only suffer fundamental misunderstandings of how knowledge is produced in most countries today, but also they may misallocate resources that support scientific research that is the basis for innovation and development. By contrast, our analyses in the selected country case studies of China, France, Germany, Japan, Qatar, South Korea, Taiwan, the United States, and the United Kingdom show that the university has in fact increased its output, related to its internationalization and rising collaborations across borders, be they geographic, political, cultural, or organizational. Indeed, Adams (2013) finds that internationally collaborative work from the United States and the United Kingdom is more likely to be cited than purely domestic research, with the scientific cutting edge now driven by collaborations among leading research groups working in multiple cultural contexts, albeit usually within the *lingua franca* of English.

Limited Empirical Studies on Science Production

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 the decades since 1980 (Adams, 2009; Adams, Black, Clemmons, & Stephan, 2005; Bornmann & Mutz, 2015; Godin & Gingras, 2000) or the era since 1990 (Bornmann, Wagner, & Leydesdorff, 2015). Moreover, 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 (Meo, Al Masri, Usmani, Memon, & Zaidi, 2013; Meo, Usmani, Vohra, & Bukhari, 2013; Teodorescu, 2000). This limited perspective has severely reduced the potential of comparative and historical case studies that directly examine how different institutional models evolved in historical context – and the consequences for research capacity at national and organizational levels. Yet this is necessary if we are to understand the long-term developmental factors that determine regional and national capacity-building. If we hope to make meaningful comparisons across countries, an understanding of the development within the cases is necessary; this volume collects diverse case studies in this vein.

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). Increasingly, with the advent of supercomputers, the outputs of even entire research associations, types of organizations, and countries can be aggregated, which the contributions in this volume do. These databases are used as a tool to gain insights into scientific publication output in general, the integration of scientific communities and their expanding networks, and internationally visible research results (Ball & Tunger, 2005). Bibliometrics as an independent field of research deals with the statistical analysis of bibliographic information, especially with study of authors, publications, and organizations. The French term *bibliométrie* was introduced by Paul Otlet in 1934, gaining worldwide fame decades later in 1969 when Alan Pritchard defined the English term *bibliometrics* as "the application of mathematical and statistical methods to books and other media of communication" (Pritchard, 1969, p. 348), providing an alternative to the earlier common term "statistical bibliography." Other researchers define bibliometrics as a discipline more narrowly as the quantitative study of works reflected in bibliographies (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, more broadly, bibliometric research is considered to include all aspects and models of science communication, storage, distribution, and publication (Glänzel & Schöpflin, 1994).

Publishing and citing references as fundamental scientific activities have been done for thousands of years, even if not in the elaborate form of scientific references of today (Jovanovic, 2012). Outstanding early bibliometric analysis have been conducted by such scientists as Alfred J. Lotka (1926), Samuel C. Bradford (1934), and George K. Zipf (1949). Further milestones in the history of bibliometrics in the 1960s and 1970s include the first publication of the Science Citation Index (SCI) that Eugene Garfield developed in 1963 (Garfield, 1964), and publication of the foundational works of Derek J. de Solla Price (1961, 1963). These works, among others, popularized bibliometrics worldwide and helped to establish it as an independent research field (Glänzel, 2003). The tremendous increase of computing power and the invention and tremendous (and ongoing) expansion of citation indices has made it much easier for researchers to analyze global publication and citation patterns.

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

Today, two major providers dominate the world market of scientific data, mainly in the form of journal publication data gathered in citation indices: Thomson Reuters (TR) (now: Clarivate Analytics) with its Web of Science and Elsevier with its Scopus database. These document the valorization of certain scientific products as valuable via the selection of journals, calculating "impact factors" (a measure that reflects the yearly average number of citations to recent articles published in that same journal), and collecting citations and cross-references. More inclusive than ever before, Scopus and the Web of Science reach across the world to gather scientific metadata in all fields and in many different languages, even if the most leading journals – especially in the STEM+ fields analyzed in this volume—publish in English.

The two main databases for abstracts and citations of peer-reviewed literature, the TR's Web of Science (WoS) and Elsevier's Scopus, were compared to discover differences in coverage and selectivity.[1] The results show that the two databases exhibit similar trends in coverage (becoming more inclusive via the gradual, continuous addition of journals) and in overall rising production. We compare whole counts from each database for 10 countries – China, France, Germany, Great Britain, Japan, Russia (USSR), Qatar, South Korea, Taiwan, and the United States. 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 of these countries between the WoS and Scopus data follows: China (0.993), France (0.958), Germany (0.956), Great Britain (0.970), South Korea (0.998), Japan (0.979), Russia (USSR) (0.545), Qatar (0.983), Taiwan (0.998), and the United States (0.959). In most countries, the aggregate publication volume in Scopus surpasses that recorded in WoS, and we find more publications in Scopus than WoS for each country through 2011; however, this coverage in Scopus is related to more different types of publications and non-STEM+. Similar trends, whether increasing or decreasing coverage for each country, were found for 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 (on Russian and Chinese university-based science, see Oleksiyenko, 2014). Thus, despite challenging questions of representativity in the overall coverage of the major databases, they are quite similar, which is crucial for comparing the results presented here with analyses on the basis of Elseviers' Scopus. Other frequently used databases, such as Google Scholar or academic social networking platforms like Academia.edu or ResearchGate.net, as user-driven and user-dependent sources of bibliographic data, are even more selective than WoS or Scopus and provide unreliable representations of scientific sources.

Today, the Web of Science indexes 12,000 journals, roughly equal to a quarter of the regularly published research serials globally and representing those leading journals that attract more than 95% of the citations (cross-references) among scholarly articles (Adams, 2011, p. 6). Thus, while highly selective, the indices do represent those journals that review, collect, and present the research with the greatest (potential for) scientific impact.

Due to the transformation and global spread of the scientific landscape, bibliometric analyses are applied as an evaluation instrument of national and organizational scientific capacity (Ball & Tunger, 2005). As part of research evaluation systems (Whitley & Gläser, 2007) or performance-based research funding systems (Hicks, 2012; Roberts, 2006), these measures of science have become regular instruments of scientific management and science policy, as they transform the governance of research and patterns of scientific production around the world. 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). More than ever, policymakers (attempt) to use big data to monitor the performance of universities and other science-producing organizations; however, the most visible focus in key media has been on ranking the world's top higher education organizations, usually based upon a few quantitative indicators and reputational estimates instead of systemic and comprehensive comparisons (Espelund & Sauder, 2007, 2016; Hazelkorn, 2011). In many countries analyzed here, we show that, in fact, the research university contribution to scientific output has increased proportionally to other organizations in the context of pure exponential growth and the broadened inclusivity of the key databases gathering and cataloging scientific information.

METHODOLOGY AND DATA

The SPHERE project's centerpiece involved the creation of a huge dataset representing all scientific journal articles published in peer-reviewed journals within Thomson Reuters' SCIE collection of STEM+ journals between 1900 and 2011. The following section describes how this dataset was created through years of archival research and (re)coding.[2]

Data Source, Sampling, and Coding

The chapters in this book are based on analyses of Web of Science publication data (SCIE) compiled and sold by Thomson Reuters (TR) and its precursor organizations covering the years from 1900 to 2012 and obtained by the research team in Fall 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 analyzed. We focus here only on research articles (of varying length), not on other types of publication in the database, such as reviews or letters.

For SCIE data from 1900 to 1970, we found that the majority of research articles[3] were missing information on organizational 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 journal articles for each of the relevant data years by directly consulting the scientific journals – in archives, libraries as well as Internet databases – to make reliable population estimates.

In sampling, we proceeded as follows. First, we selected journals[4] 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 (Other). 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 "Science," 10% into "Technology," 55% into "Health," and 0 into "Other." 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 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 ("Accession Number" in the WoS 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 names and affiliations. If an author's name was not identifiable through Internet research, the WoS 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 WoS online portal nor searching other databases was successful, that case was coded as missing.

Another situation required us to replace a few journals after the first round of randomized 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 WoS website. For example, in the Journal "*Physical Review A*" in 1970, there were 429 articles based on the search result on the WoS 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 further random selection.

It is a common critique of the WoS data that journals written in English are more likely to be included in its database than those with contributions in other languages. During the coding process, we 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. So as not to exacerbate 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 successful Internet searches for author information.

The data purchased from TR also included a small proportion of journals not traditionally considered to be in STEM+ fields. TR indicated that some journals are indexed in both the Science Citation Index Expanded (SCIE) and the Social Sciences Citation Index (SSCI) due to their cross-disciplinary nature. We did not exclude these multi disciplinary journals in our analysis, especially for the years from 1980 to 2011, due to their inclusion in SCIE and their relevance to STEM+ researchers.

How SPHERE Counted Collaboratively Written Research Articles

Especially multiple authorships and cross-national comparisons and collaborations give rise to technical problems in counting publications (Gauffriau, Larsen, Maye, Roulin-Perriard, & von Ins, 2007, 2008). When counting total publications worldwide, we used the number of unique research articles regardless of the organizational affiliation and address(es) of each article. That is, for global totals, any single-authored or collaboratively written 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 for world totals.

When counting publications in multiple regions or across countries, things necessarily become more complicated. Consider a publication with the following co-authors: 2 from the United States, 1 from Germany, and 1 from France. There are three typical 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 regardless of the number of authors. 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, that is, the sum of country numbers exceeds world total due to international collaborations (that have been increasing considerably in recent decades). This is especially important to consider when counting publications by regions. That is, if one is interested in comparing regional production (e.g., North America and Europe), then the above identified paper should be counted as 1 for North America (United States), and 1 for Europe (Germany, France).

A second option is called fractional counting, 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) would receive ⅓ credit. Alternatively, the number of authors working in a country can be taken into account. For the above publication, the United States receives ½, Germany receives ¼, and France receives ¼. Of course, given the global flows of scientists, this does not indicate the nationality of the researcher(s). Furthermore, researchers increasingly have multiple affiliations, collaborations are rising exponentially, and the number of authors in total and on each paper is growing. Having researched the organizational addresses that reflect where the research was conducted, we assign the credit on that basis. We selected the whole counting method for the country comparisons shown in this volume.

Transformative Regime Change: The Dissolution or Unification of Countries

Because of the significance of an author's country affiliation – not their actual citizenship status, but rather the host country of the research organization with which they are affiliated – for our analyses, the dissolution or unification of countries required careful attention (e.g., the former Soviet Union breaking up into many countries or Germany after unification). Because of the lag time between research completion, article submission, and article publication date, a decision rule was adopted that allowed an article to be attributed to the former country up to three years after the date of transformative political regime change. For example, the USSR was divided into 15 nations on December 26, 1991. Based on the 3-year rule, USSR in TR data was coded as such through the end of 1994.

If an article attributed to an author from a research organization in the USSR appeared in 1995 and afterwards, the country affiliation was recoded into the correct current country name by cross-checking the organization or city 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. A contrary case is unification of multiple states. When occupied Germany was divided into the Federal Republic of Germany (West Germany) and the German Democratic Republic (East Germany), articles were thus coded. During the period prior to 1949, all articles published by scientists in research organizations in the territories belonging to Germany were counted under "Germany." After reunification in 1990, articles from authors in both parts of the country were again attributed to "Germany." Further, precise coding rules are available upon request from the authors.

COMPARING RESULTS

We now turn to selected comparisons of the case study countries, beginning with an historical charting of the evolution of worldwide STEM+ publications from 1900 and continuing until 2011, driven largely by the countries analyzed in-depth in this volume. This overarching analysis discusses key trends in the century of science for the whole world before we turn to the chapters devoted to single or comparative case studies of the institutionalization of higher education and science systems and research policy.

The country cases studied in-depth over the duration of the project included Belgium, China, France, Germany, Japan, Luxembourg, Qatar, South Korea, Taiwan, the United Kingdom, and the United States, not all of which can be presented in this volume (for Belgium and Luxembourg compared to France and Germany, see Powell & Dusdal, 2016). 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 SCIE publications across the 20th century up to the current decade shows major shifts in the regional development of universities and science – and the particularly strong recent growth in China and other East Asian countries (see also Shin, Postiglione, & Huang, 2015). Regarding the United States, the largest science producer for decades, its world-leading capacity is built upon an unusual combination of mass and elite, academic and practical, education in one complex, highly differentiated higher education system, growing especially strongly since the World War II (Labaree, 2017). In Europe, our comparisons of higher education and extra-university research institutes show that these different organizational forms have contrasting contributions in the traditionally top science producers of France, Germany, and the United Kingdom. Despite the different relative significance of these organizational forms in these contexts, both are crucial to overall scientific productivity in many countries. Further, science productivity in Japan has been shown to depend not only on the elite universities, but also on the range of national and regional universities throughout the country. Our research on South Korea shows the significant contribution of private universities and investments to the extraordinarily fast growth of that country's higher education and research systems. Qatar, one of the most rapidly growing countries anywhere in the world has, within 15 years, developed a comprehensive national research system, albeit on a small scale befitting its size. All of these country cases examined thus far, most discussed in the following chapters, show how higher education and research, as key pillars of the knowledge society, have expanded dramatically since 1900, yet beginning in different eras.

Global Mega-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, pure exponential growth would slow down, resulting in lower rates of increase in production at the upper limit of a logistic curve. Yet they were mistaken. The findings presented here show that, in fact, "big science" was itself transformed by unprecedented production, with exponential growth continuing through to the contemporary era. This remarkable growth reflects two contrasting and simultaneous trends – rising competition across nations and international collaboration among scientists.

Global mega-science has been powered by strong European science systems that pioneered discoveries over the centuries and were rebuilt after World War II. Another pillar is North American investment in science capacity rising over the 20th century, with the United States and Canada among the most prolific countries globally. 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 their overall contribution to global production of journal articles is small (Crist, 2017; Wiseman, Alromi, & Alshumrani, 2014). For example, as Crist demonstrates, 75% of Qatar's entire research output between 1980 and 2011 involves collaboration between a locally based author and an author based outside of Qatar. Countries in other regions also participate in this globe-spanning expansion of collaboration within a diversity of forms of university structures, including university networks and international branch campuses.

Global Differentiation and Competition

If in 1900 the top 10 countries in the world published 87% of all papers, in 1950 their proportion increased slightly to 90%, but by 2000 this had dropped to around two-thirds (69%) and by 2010 to only three-fifths (63%). 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 (see Mihai & Reisz, 2017). 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. The case studies analyzed in-depth in the volume focus on top producing countries, such as the United States and China, strong mid-sized producers in Europe and East Asia, and a small, but growing producer, Qatar, in the Middle East.

The global center of gravity of SCIE publications shifted over the century, as measured by calculating the annual weighted geographic centroid of each country by the number of SCIE publications produced in that country (Zhang et al., 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 20th century, France, Germany, the United Kingdom, and the United States largely dominated scientific production, with the last in marked ascendancy (Fernandez & Baker, 2017; Powell & Dusdal, 2017). Over the next 40 years, U.S. universities, emulating the model of the German research university preeminent in the early 20th century, became increasingly productive (Baker, 2014; Geiger, 1986). But despite the victory of World War II and massive investments in higher education and science (Kleinman, 1995; Labaree, 2017), American dominance waned due to the renewal of Europe's diverse higher education and science systems.

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, toward Europe and, in most recent decades, East Asia. What the SPHERE results show, insufficiently recognized earlier, is that these trends of global diffusion and regional differentiation began much earlier in the 20th century than commonly understood. This volume contributes to the literature presenting case studies that analyze data – painstakingly recoded in years of archival and Internet-based research – over a much longer period of time than previous studies, which have tended to study scientific production over shorter time spans; typically a few recent decades (see subsection "Limited Empirical Studies on Science Production").

Today's global competition for scientific impact is no longer solely taking place in the Atlantic world. Rather, it is one that encompasses the entire Northern Hemisphere, with the scientific superpowers – the United States and China – competing with each other, along with the many less populous European countries with their well-established and highly productive science systems. Although growth in SCIE publications decreased in Japan during the 1990s, the rise of other Asian countries – in particular China and South Korea (which ranked 11th in 2011, with 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 (Kim & Choi, 2017; Shima, 2017; Zhang et al., 2015; Zhang, Sun, & Bao, 2017). 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 United States, which has posted an average annual growth one full percentage point lower than the world average since 1980s. Yet simultaneously with broadened competition between countries, organizations, and research groups, another global pattern is also remarkable for its strength, namely the inexorable rise in collaborations between scholars and scientists across cultural and political borders.

International Collaboration: Boundary-spanning Dynamics

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 pure 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 author alone. Indeed, the number of coauthored papers has more than doubled since 1990 and over a third have authors conducting research in multiple countries. Obviously, the scientific landscape exhibits myriad linkages, as the search for new knowledge has always crossed borders. If growth is common to all countries, established economies collaborate more than rapidly growing scientific nations, such as China, India, or Brazil; furthermore, the largest countries, including the United States and China, do not collaborate as much as do European scientists (Adams, 2013). Europe with centuries of experience in navigating multicultural and multilingual communication in scientific debates, the smaller size of many of these higher education and science systems, and considerable mobility across the Continent facilitates cross-cultural collaboration. In no small measure, the programs of the European Union support the communication and exchange at the heart of this dynamic development. For example, the Erasmus Programme facilitated 3.3 million student exchanges and 470,000 staff exchanges in just a quarter-century. The European Research Council (ERC) finances "frontier" research throughout the Continent and creates new supranational scientific elites (Flink, 2016; Hoenig, 2017; König, 2016). And the Framework Programme of EU Research Funding explicitly supports cross-border collaborative research projects to establish sustainable research networks and coordinated research agendas (European Commission, 2015; Zapp, Marques, & Powell, forthcoming).

The well-documented rise of China and the less well-known renewed scientific ambitions in the Middle East, millennia after the previous peak of Islamic science (on contemporary publication patterns in the Islamic world, see Sarwar & Hassan, 2015), provide new opportunities for the production of science and for international collaboration. As investments in international branch campuses and knowledge hubs in the Arabian Gulf countries attest (Crist, 2017; Miller-Idriss & Hanauer, 2011; Wiseman et al., 2014), more than ever higher education and science are becoming global enterprises in which collaboration across borders are key sources of innovation. If competition is never far from the rhetoric of policymakers and science administrators, individual research teams and scientists seem motivated by the belief that collaborating on the cutting-edge problems in their fields provides a successful strategy to accomplish more and to make their results more visible beyond their own cultural context.

The unprecedented, exponential growth in article production reflects the increased importance of higher education and science in countries worldwide. The shifting center of gravity away from the United States 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 successful intercultural communication and the building of international 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 (Kosmützky & Putty, 2016).

Connections between Science Production and Economic Prosperity

The concurrent shift and eastward movement of the centers of science production and economic prosperity (Dobbs et al., 2012) since 1950s are not surprising. The relationship is likely mutualistic. In "the schooled society" (Baker, 2014), growth in all levels of education have not only transformed learning across the life course and knowledge production, but also whole professions and occupational groups, with considerable impact on economy and society. And as education-driven economic development provides resources necessary for research and scientific production, this in turn spurs further economic growth. Although no simple model of causality can be inferred from this concerted change, decades of economic research have convincingly shown that education, science, and technology have all played crucial roles in economic growth (Goldin & Katz, 2009; Romer, 1986; Solow, 1957). Recently, studies have addressed this issue for OECD countries, asking in which direction causality flows, and finding unidirectional causality from research output, measured in articles published, to economic growth for the United States, Finland, Hungary, and Mexico, but the opposite – from economic growth to research articles published – in Canada, France, Italy, New Zealand, the United Kingdom, Austria, Israel, and Poland; furthermore, none for the other countries (Ntuli, Inglesi-Lotz, Chang, & Pouris, 2015; see also Mihai & Reisz, 2017).

Investments in science and education are obvious explanations for the determination of scientific productivity. Indeed, the most productive countries in the world of STEM+ are countries with high values of per capita GDP and high investments in education and science. Yet while scientific giants like the United States or China account for a high proportion of absolute global scientific journal article production, the most productive countries on a per capita basis are a few smaller ones (e.g., Israel, Scandinavian countries, and Switzerland) (May, 1997; Mihai & Reisz, 2017). Highly internationalized, 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 (e.g., Belgium, see Powell & Dusdal, 2016). Thus, global scientific capacity-building is not only the province of large countries. 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 considerable differences in scientific output.

Indeed, across the countries examined in-depth in the volume, we find historical and cross-national variation in the "research intensity" or the gross expenditure on R&D as a proportion of GDP (Fig. 2). If South Korea leads today, this reflects tremendous growth over just a few decades. Japan, still investing a similar proportion as the United States and Germany in the 1980s, has risen over recent decades. Taiwan has also increased its research intensity, but at a lower level than the other East Asian countries. Neck-and-neck, Germany dipped below the United States in the period following reunification, but has since risen to around 3%, the 2020 target set by the European Union, and is above the United States. Just below the OECD average (2.4%), France shows a research intensity of 2.3%, followed by China, which has also followed the trend of its East Asian neighbors, but at lower level (2%). The United Kingdom, equal to the OECD average and France in the mid-1980s, has

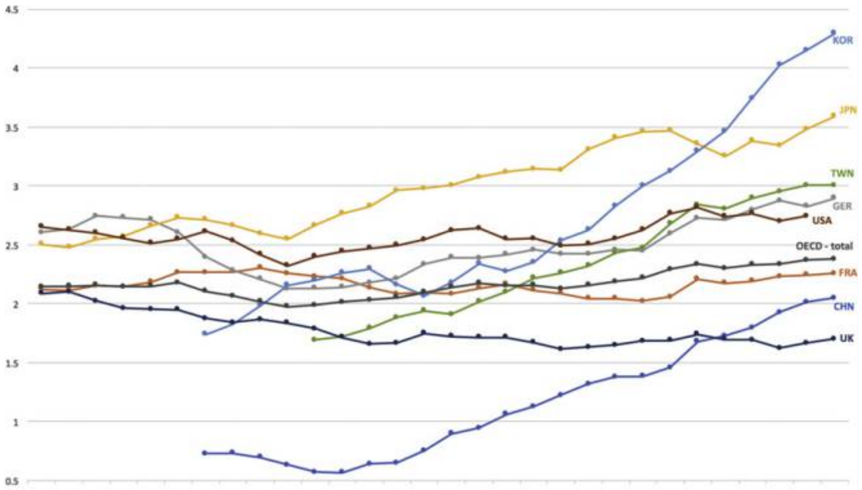

Fig. 2. Research Intensity in Select Case Study Countries and OECD Average (GERD as a Proportion of GDP), 1985–2014. *Source*: OECD.Stat (2017): Main Science and Technology Indicators. Accessed on October 1, 2017.

dropped off to only 1.7%, exhibiting by far the lowest research intensity in this group of high-producing science countries.

The research intensity indicator is widely used to gauge the volume of investments in R&D, yet these countries' economies have different scales. Turning from the input measure to outputs – namely volume of published STEM+ papers in the SCIE – we standardize on the basis of overall population and, in a more proximal measure, the number of researchers in full-time equivalents (although here distinctions cannot be made by discipline, circumscribing the specificity of this indicator). Comparing the volume of papers produced across a subset of countries analyzed in the SPHERE project reveals quite a different picture than that of the input side. Here, the United Kingdom, the country with the lowest research intensity, has the most publications per million inhabitants, clearly reflecting its highly internationalized and very productive universities as well as the enormous advantage of the English language and the large number of journals edited and published there. Generally, universities seem to provide the most prolific climate for research, more so than extra-university research institutes (May, 1997), despite the fact that both Germany and France invest considerably in such institutes. Quite a bit lower, Germany, the United States, and France have similar results, again with varying expenditure levels. Japan exhibits a relatively similar trend to those countries, but with flat productivity since 2000. In distinct contrast, South Korea manifests a similar extraordinary growth curve in its publications as in its R&D investments, nearly quadrupling in less than two decades. China, with its vast population, has nevertheless risen to around 100 such publications per million inhabitants annually. The range between these top science-producing countries remains stark; more than a factor of six between China and the United Kingdom (Fig. 3).

Turning now to the development of the ratio of publications to 100 researchers (full-time equivalents, FTE) also shows considerable spread across these countries in different regions and contrasting institutionalization pathways of higher education and science (Fig. 4). Indeed, confirming the analysis by Adams (2013), the United Kingdom stands out as much more productive per researcher than the other countries for the entire period, with 27 published papers in 2010 (albeit with a stark drop in 2005), reflecting that country's multiple advantages, including hosting among the world's strongest and internationalized universities, operating naturally in the English language, benefiting from being a center of scientific publishing, and perhaps also resulting from an elaborate research evaluation system developed over decades that has pressured academics to produce more research articles than other forms of scientific output (Marques, Powell, Zapp, & Biesta, in press). Germany (23 published papers), France (22), and the United States (22) now cluster when measuring their papers per 100 researchers (FTE), with Germany catching up on this measure. Taiwan is the most productive of the four East Asian comparator countries, with 17 published papers in the SPHERE database per 100 FTE

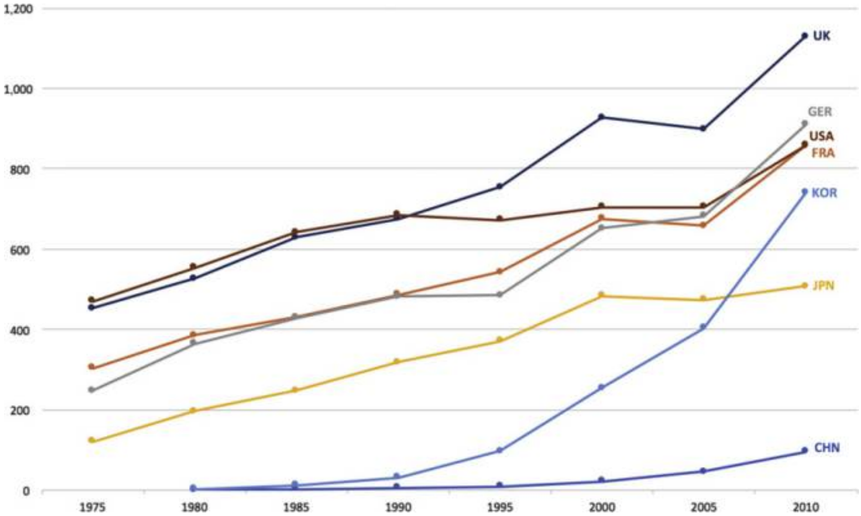

Fig. 3. Publications (SCIE) per Million Inhabitants, 1975–2010. *Source*: OECD. Stat (2017): Main Science and Technology Indicators. Accessed on October 1, 2017; SPHERE project database of SCIE publications (Thomson Reuters' Web of Science).

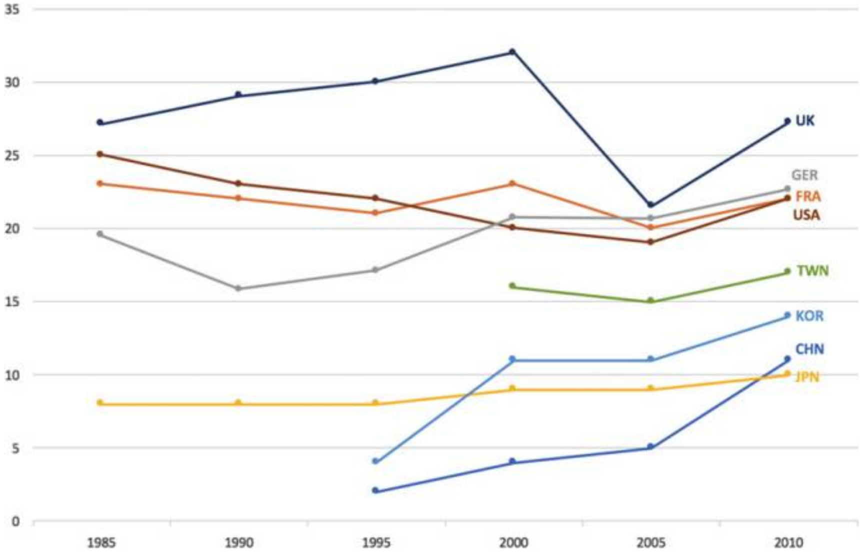

Fig. 4. Publications (SCIE) per 100 FTE Researchers, 1985–2010. *Source*: OECD. Stat (2017): Main Science and Technology Indicators. Accessed on October 1, 2017; SPHERE project database of SCIE publications (Thomson Reuters' Web of Science).

researchers. South Korea (14) and China (11), with their recent extraordinary rise is absolute production, have most recently overtaken Japan (10), which exhibits stability over the period with a recent uptick in this publication to researcher ratio.

Such historical and spatial variance in key indicators of research and development, measuring both inputs and outputs, demands further investigation, to which we turn in the following chapters.

CHAPTER OVERVIEW

In his *cross-country comparative chapter*, Mike Zapp examines global higher education expansion and the growth of science. He charts the institutionalization of higher education systems in seven countries from 1945 to 2015, exploring various trajectories of higher education expansion and its political and social conditions in China, Germany, Japan, Qatar, South Korea, Taiwan, and the United States. The analysis relies on longitudinal and cross-sectional data gleaned from the World Higher Education Database, UNESCO, and the OECD. All these countries have seen remarkable higher education expansion in the 20th century in terms of enrollments and the foundings of universities, with particularly strong growth over the immediate post-World War II period and since 1990. For the particular case of STEM+ fields examined here, the author shows that in those higher education systems in which growth took off relatively late, universities oriented toward the STEM+ fields are more dominant than in those with a longer history, reflecting the humanities and professions orientation of early universities. Countries with more recently institutionalized higher education systems stress technological development more than those that look back on multiple centuries of higher education expansion with their canonical legacies. Comparing these highly dissimilar countries nevertheless reveals important common patterns, and the variable paces of growth can be explained by national social and political factors driving the institutionalization of higher education and research.

Focusing on the three key science-producing countries in *Europe*, Justin J. W. Powell and Jennifer Dusdal compare growth in scientific productivity and institutional symbiosis between research universities and extra-university research institutes in France, Germany, and the United Kingdom. The authors chart significant growth in universities and in scientific productivity over the 20th century. The analysis presents the development and current state of universities and research institutes that bolster Europe's leading position in global science. Ongoing internationalization and Europeanization of higher education and science has been accompanied by increasing competition as well as collaboration. Despite the political goals to foster innovation and further expand research capacity in all three countries, in cross-national and historical comparison shifting research policies (and the resultant level of R&D investments) do not fully account for the differential growth of scientific productivity. Based on a comprehensive historical database, this analysis uncovers both stable and dynamic patterns of productivity from 1975 to 2010 in France, Germany, and the United Kingdom – the three major European science producers. Measured in peer-reviewed research articles collected in Thomson Reuters' SCIE, we also identify individual organizations leading in research output. These results show the varying contributions of different organizational forms, especially research universities and research institutes, with universities' contribution nearly half but rising in France; ultrastable in Germany at four-fifths, and growing and around two-thirds in the United Kingdom. Contrasting institutionalization pathways created the conditions necessary for continuous, but varying growth in scientific productivity in the European center of global science.

Crossing the Atlantic, Frank Fernandez and David P. Baker examine science production in the *United States* throughout an era of massified higher education and the "super research university." The authors argue that U.S. scientific production resulted from an unexpected synergy between the rise of research universities, particularly public ones, and the comparatively rapid development of mass schooling, leading to mass access to higher education. From humble beginnings, U.S. universities organized faculty into modern academic fields, and their members established national scientific societies. Across the country, expanding primary enrollments gave way to the creation of the comprehensive high school, and near-universal secondary school enrollments led to mass higher education. Universities not only offered access to broad segments of the public, they also added to the U.S. – and global – stock of scientific researchers by training large numbers of new PhDs in STEM+ fields. Toward the end of the 20th century, some observers sought to characterize universities as weak organizations; they speculated that universities' share of scientific publications would decline and that universities would be outpaced by private companies. Yet academic researchers continue to not only produce a majority of U.S. scientific publications, they also collaborate with non-university partners to author more than three-quarters of all STEM+ scholarly works. The research university and the inclusive educational practices originating from public institutions over the last century serve as the backbone of American scientific production.

Turning next to Asia, Kazunori Shima evaluates science productivity in *Japan* by focusing on the so-called unsung heroes of the Japanese university system, which – as in the other countries mentioned thus far – forms the core of knowledge production. Other producers, including business enterprises, make up the second largest group, but the number of articles they published has fluctuated. Top national universities (former imperial university & pre-World War II universities) have been the main scientific producers, but the second-tier national universities (post-World War II universities) sustained Japan's world ranking of scientific productivity into the 2000s. Yet Japan was the only major country that did not increase the number of STEM+ articles it produced between 2005 and 2010, and as a result, Japan went from being the second-largest knowledge producing country in 1990 to the fifth in 2010 worldwide. Unsurprisingly, as funding from basic government 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 policymakers in Japan that competition is inherently beneficial for scientific productivity and emphasize the importance of in-depth analyses of different organizational forms and research capacity within the university sector.

Examining *China*, the main competitor nation to the U.S. in overall, absolute publications, Liang Zhang, Liang Sun, and Wei Bao show the transformation of higher education and research and development policies since 1949. Providing a thorough historical overview of policies that have governed and guided scientific research in China, the authors divide this historical period into four stages, each with distinct R&D policies: a period of socialist transformation (1949–1955), a phase of struggle for higher education and research development in a rapidly changing political environment (1956–1965), the lost decade of the Cultural Revolution (1966–1976); and, since 1976, a phase when major national policies have significantly promoted scientific research throughout China. Using data from SPHERE and a set of Chinese research universities, the authors demonstrate changes in scientific publication rates concurrent with these policy reforms and programs. This analysis suggests that there is a tight connection between national policy and scientific research productivity in higher education in China.

Taking a similar perspective, Hyerim Kim and Junghee Choi examine the significant contribution of private universities to higher education and research in *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 so crucial elsewhere. Research is a relatively new mission for Korean universities, as through the 1980s, the Korean government saw colleges and universities as primarily providing human resources for national industries, less as the organizations responsible for generating scientific research. In order to investigate how especially private universities have contributed to the growth of Korean higher education and research, this chapter compares student enrollments and science production by university-based researchers over time. In Korea, the proportion of publications by private universities has exceeded that of national and public universities since 1998, which challenges the conventional wisdom that public universities are per se better suited to pursue basic (and perhaps less immediately profitable) scientific research because of their orientation to the public interest.

In the chapter on *Taiwan*, Yuan Chih Fu elaborates the development of higher education there, also comparing the relative contributions to scientific productivity of different types of organizations, including higher education and the Academy of Sciences (Sinica). To fully appreciate the development of technological innovation in Taiwan, it is crucial to understand the rise of Taiwanese universities. Taiwan has one of the most intensely schooled populations in the world, thus even though its scale is comparatively small, its research power is considerable. Historically, the development of higher education and science capacity-building focused on cultivating a centralized, publicly funded system. The massification of Taiwanese higher education allowed universities to expand student enrollments and accommodate more researchers. In addition to the expansion of higher education, internal changes within the university sector also spurred scientific production. 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 PhD holders from top global universities as faculty. Through internal and external policy changes, Taiwan changed the way its university-based researchers conduct and publish research.

Turning to the Middle East in a final case study chapter, John T. Crist analyzes the rapid development of a national research system in *Qatar*. This small desert nation, a peninsula in the Arabian Gulf, is at the forefront of a contemporary renaissance in science across the Arab and Islamic world. This is a remarkable achievement because Qatar has only recently developed its higher education sector and is among the latest entrants in the global competition of science production. The first and only national university was established in 1978, shortly after formal independence from Britain; 20 years later, Qatar franchised the development of higher education via international branch campuses to leading Western 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. 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; indeed, the country profits from highest degrees of international collaboration. A significantly more difficult and long-term goal than building a research infrastructure to attract global science to the Gulf is the nurturing of indigenous capacity. Given Qatar's dependence on foreign scientific labor, high rates of international collaboration will persist even as the regional hub develops.

Exploring the complex relationship, noted above, between *economic and scientific development*, Iris A. Mihai and Robert D. Reisz examine productivity in relation to economic development. Throughout the 20th century, the overall development of world science as seen in the numbers of STEM+ publications was exponential. Alongside the massive rise in the number of scientific publications, another important phenomenon was the globalization of science. The wealth of countries, measured by per capita GDP, has an essential impact on scientific capacity, but wealth alone does not explain the differences in scientific output. While scientific giants such as the United States and China are naturally the largest contributors to absolute article production across the globe, the relatively most productive countries are in fact much smaller ones. Mihai and Reisz discuss how the institutional settings in which research is conducted affects countries' scientific productivity, concluding that the relationship between economic wealth and knowledge production is mutualistic, with the scientific advance of earlier times facilitating economic development, which in turn provides resources necessary for further scientific study, which in turn spurs further economic growth. To disentangle the complex institutional factors responsible for contrasting higher education and science systems and the diversity in scientific productivity, however measured, requires in-depth analysis of country contexts, provided in this volume, including the different institutional environments and organizational forms that provide the resources within which scientists conduct their research.

DISCUSSION AND OUTLOOK

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 was revealed in particular countries. The authors adopted a mixed methods approach to analyze institutional models of higher education development, research policy, and science capacity-building over time and the consequences thereof for scientific production measured in longitudinal quantitative analyses of peer-reviewed papers published in leading (indexed) journals. The contributions focus in particular on the two organizational forms responsible for the vast majority of state-funded research, namely research universities and non-university research institutes of various sizes and operating in diverse associations. Read together, the chapters demonstrate the considerable differences across time and space in the institutional settings, organizational forms, and organizations that produced the most cutting-edge research across the 20th century and up to 2011.

The analyses illustrate how differences in national models in developing research universities and institutes explain long-term cross-national trajectories in system development and 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 World War II. In Europe, our comparisons of higher education and research institutes show that these different organizational forms have contrasting contributions in France, Germany, and the United Kingdom – traditionally top science producers. Despite the different relative significance of these organizational forms in these Western European countries, research universities are most 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 just 15 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.

Among the potential beneficiaries of the project research results presented in this volume 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 higher education and R&D. Analyses and discussion of the presented trends and patterns in productivity – depending on the structures and investments in R&D – will also profit scientists themselves as they reflect on their own contexts and conditions for scientific work and publication constraints and opportunities. In terms of research communities, scientists involved in bibliometrics, science studies, and neo-institutionalists who chart the massive expansion of science production and collaboration across the globe may engage with these results. 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 to illuminate issues of quantity and quality in publishing scientific discoveries.

Higher education, and in particular research 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 global producers of STEM+ research – including China, Germany, Japan, France, Canada, Italy, India, and Spain – there is limited longitudinal, multi-level or explicitly comparative research. Furthermore, many other countries that are developing their research capacity and these patterns should be the subject of future research, for example the case of Qatar. Especially given the rise of international collaborations, alongside competition, empirical studies should be – indeed must be – comparative to capture the cooperative ventures and exchange of ideas necessary for innovative research.

While the SPHERE project members invested tremendous efforts to recode especially the historical data (1900–1975) through considerable archival and Internet-based research, limits of time and access to archived journals circumscribed the geographic and linguistic scope of these historical analyses. To ensure the reliability of the analyses, we conducted preliminary comparisons of the TR SCIE and Elsevier Scopus databases, yet these comparisons should continue to be done systematically to ensure reliable trend analysis – and the selectivity of these mainly Anglophone, Western databases acknowledged. Future research should extend horizontally beyond SCIE to include all the disciplines and fields of scientific inquiry and vertically within specific disciplines (and journals) to better understand in-depth publication patterns and trends. The wide-ranging effects and often unintended consequences of research evaluation systems, rankings and ratings, and other forms of competitive comparison must be analyzed for disciplines, fields, organizations, departments, and scientists, with future research not focused solely on STEM+. Such work should utilize new data collection methods to improve measurement of science produced in diverse languages and with different formats (Internet-based, books, patents, etc.). Network analysis of international collaborations promises to illuminate the processes that lead to scientific discovery and publication.

To conclude, we have shown that "big science" has been transformed by unprecedented production worldwide since the 1950s. We can now speak of "global mega-science." Pure exponential growth in article production reflects the increased importance of higher education and science worldwide, for economy and society. Despite major wars and global economic crises since 1900, there has been no lasting decline or even saturation 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), examined in this volume, are in direct competition. Yet simultaneously with this rising competition, we find vastly increased collaboration across national, linguistic, and organizational boundaries. Information technology and accessible international travel (that has given rise to vast conference participation and educational and scientific exchange) have extended the global reach and relevance of individual scholars and facilitated global research projects in diverse organization forms and across the disciplines.

Still dominant in absolute figures, the United States suffers from relative decline in scientific productivity, as especially Asian and European countries invest heavily in their national higher education and research capacity. Newer competitors such as Qatar attempt via massive investment in university and R&D structures to play relevant roles in global science. Wealthy and internationalized smaller states with strategic investments contribute disproportionately to overall productivity. Reducing concentration among a few top producers, more and more countries have joined the enterprise of science, producing cutting-edge papers in the STEM+ fields. Such a worldwide scientific enterprise requires the sites of research capacity-building to fit into global production flows and demands infrastructures that facilitate collaboration, which has also grown exponentially over the past several decades. Indeed, alongside 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 scientific academies). Research and development requires investment not only in cutting-edge campus facilities or laboratories, but also in the networks, connections, and exchanges that facilitate discoveries – and have, whatever the difficult-to-ascertain value of any individual article – led to such expansion in the publication of scientific results in peer-reviewed journals.

NOTES

1. We are grateful to Kazunori Shima for his efforts in comparing systematically the coverage of these two key databases.
2. The authors would like to especially thank Jennifer Dusdal, Yuan Chih Fu, and Seung Wan Nam for their dedication in coding and data analysis for the duration of the project, from 2012 to 2015, coordinated and hosted at Georgetown University School of Foreign Service in Qatar.
3. Web of Science has its own categorization of writings in their database such as research article, review, editorial, and letter, 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 = @).
4. A journal title was counted only once, no matter how many volumes or issues in each year were published.

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