

THE EUROPEAN CENTER OF SCIENCE PRODUCTIVITY: RESEARCH UNIVERSITIES AND INSTITUTES IN FRANCE, GERMANY, AND THE UNITED KINGDOM

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ABSTRACT

Purpose – Growth in scientific production and productivity over the 20th century resulted significantly from three major countries in European science – France, Germany, and the United Kingdom. Charting the development of universities and research institutes that bolster Europe’s key position in global science, we uncover both stable and dynamic patterns of productivity in the fields of STEM, including health, over the 20th century. Ongoing internationalization of higher education and science has been accompanied by increasing competition and collaboration. Despite policy goals to foster innovation and expand research capacity, policies cannot fully account for the differential growth of scientific productivity we chart from 1975 to 2010.

Approach and Research Design – Our sociological neo-institutional framework facilitates explanation of differences in institutional settings, organizational forms, and organizations that produce the most European

**The Century of Science: The Global Triumph of the Research University
International Perspectives on Education and Society, Volume 33, 55–83
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ISSN: 1479-3679/doi:10.1108/S1479-36792017000033005**

research. We measure growth of published peer-reviewed articles indexed in Thomson Reuters' Science Citation Index Expanded (SCIE).

Findings – Organizational forms vary in their contributions, with universities accounting for nearly half but rising in France; ultrastable in Germany at four-fifths, and growing at around two-thirds in the United Kingdom. Differing institutionalization pathways created the conditions necessary for continuous, but varying growth in scientific production and productivity in the European center of global science. The research university is key in all three countries, and we identify organizations leading in research output.

Originality/value – Few studies explicitly compare across time, space, and different levels of analysis. We show how important European science has been to overall global science production and productivity. In-depth comparisons, especially the organizational fields and forms in which science is produced, are crucial if policy is to support research and development.

Keywords: Scientific productivity; university; research institute; France; Germany; United Kingdom

THE ORGANIZATION(S) OF SCIENTIFIC PRODUCTIVITY

Charting huge growth in scientific productivity over the 20th century in three European countries, we analyze the development and contemporary state of research universities and institutes that bolster Europe's position as a key region in global science. Ongoing internationalization (and Europeanization) of higher education (HE) and science challenges traditional nation-based studies. In response, neo-institutional analyses have explored the powerful diffusion of worldwide ideas and norms in science (Drori, Meyer, Ramirez, & Schofer, 2003). This framework emphasizes global similarities, with (HE) expanding worldwide (Meyer, 2009) and the development of the "super research university" a powerful contributor to the "schooled society" (Baker, 2014). Despite convergence pressures due to internationalization, comparative institutional analyses show persistent differences in higher education (HE) systems as well as the diffusion of a distinctly European model in skill formation (Bernhard, 2017; Graf, 2013; Powell, Bernhard, & Graf, 2012; Powell & Solga, 2010).

Our sample of three key countries reflects the history and development of the research university as well as independent research institutes as they host the most prestigious and productive science organizations worldwide. Historically, France, Germany, and the United Kingdom (UK) have led in

organizational developments and scientific innovation. These countries differ in languages and cultures and in the resources devoted to education and science. In an era of internationalization, massive growth in the scientific output of these countries and globally simultaneously reflects competition and collaboration (Zhang, Powell, & Baker, 2015). Charting the last four decades since 1975, our comparison uncovers sustained and increasing scientific productivity in these three countries but variable institutionalization of HE and science systems, and contrasting investments in research and development (R&D).

Measured in papers published in leading peer-reviewed journals of the Science Citation Index Expanded (SCIE), the volume of scientific output differs, sometimes unexpectedly, according to institutionalized structures of HE and research. For example, the relative importance of universities, research institutes, and firms differs across the analyzed cases. The overall scientific output in science and technology disciplines, including health, increased dramatically over the 20th century, with Europe losing, but regaining its position as one of the global “center(s) of gravity” after WWII (Zhang et al., 2015). Together, these countries contribute considerably to global scientific production as their scientists publish a vast number of scientific papers. While all invest considerably in education and science at all levels, as measured in absolute terms and per capita (OECD, 2016), we find important differences in science production and productivity, especially over the post-WWII period. On the basis of comprehensive historical data of science, technology, engineering, mathematics disciplines, and health – thus, we note this dataset as representing STEM+ – we measure the volume of science produced, tracing in particular the development of research universities and research institutes, the two major organizational forms that host scientists producing peer-reviewed publications in specialized scientific journals.

The selected countries differ in research policies, HE and science systems, and internationalization. They manifest extensive collaboration and competition since the earliest academies and universities. Among all science-producing organizational forms, how much do universities and non-universities, for example, extra-university research institutes, government agencies, or companies, proportionately, contribute to scientific productivity? How do these countries, with varying institutionalization of universities, compare in their production of STEM+ research?

To address these questions, we proceed as follows: We first chart the historical evolution of different organizational forms in European science, from the first academies to universities and research institutes. Placed within global trends in science production, these strong producers have maintained their position at the core of the European center of science – and globally, despite the quantitative dominance of the United States and China (Fernandez & Baker, 2017; Zhang, Sun, & Bao, 2017). Reviewing our historical and quantitative data and methods, we present findings on developing research-producing structures and scientific productivity in France, Germany, and the UK, differentiating by

organizational form where possible. Finally, we compare across countries to better understand institutionalized systems of HE and research largely responsible for scientific productivity, and we conclude by identifying further steps for comparative research.

EUROPE: A CENTER OF GLOBAL SCIENTIFIC PRODUCTIVITY

Higher education and research, transmitting and producing knowledge in the *lingua franca* of the day, are thoroughly worldwide activities. Along with changes in the “center” of science – France around 1800, Germany from 1840, and the United Kingdom and the United States since WWI (Ben-David, 1984) – the language of science shifted from French to German to English, leading to the current dominance of journals publishing contributions in the English language. The case selection portrays the shifting significance of these three official languages as it does the legacy of earlier eras of scientific communication. Today, English everywhere provides a (necessary) common communication platform, especially in STEM+ disciplines and multidisciplinary fields.

Analyzing millions of original articles published since 1900 manifests unprecedented growth in the global pursuit of science, beginning just after mid-century and built upon contrasting concurrent trends – rising competition between and international collaboration across national borders (Zhang et al., 2015). Home to many of the oldest research universities and other organizational forms, such as academies and research institutes, Europe is at the heart of scientific productivity between North America and East Asia (on Russia and China, see Oleksiyenko, 2014). Universities and extra-university research institutes provide spaces and support for intercultural collaboration and learning and for scientific discovery, extending the massive educational expansion in societies worldwide (Schofer & Meyer, 2005), as countries capitalize on the myriad benefits that research universities bring (Baker, 2014). The earliest organizations with continuous scientific activity, such as academies, universities, and hospitals, have been joined not only by science-based companies, but also by a variety of government agencies, associations, laboratories, the military, among others (Dusdal, 2017). While originally science was dominated by Church and State, scholars and scientific organizations have gradually gained considerable independence to pursue the questions science itself defines as relevant. If the early social forms of science have been rarely studied, the successful institutionalization of science in England and France can be understood as based on “scientific movements oriented to political and social reform. For these movements, science was a model for attaining progress, objectivity, and consensus in general” (Ben-David & Sullivan, 1975, p. 205).

Today, all countries invest in HE and research and development (R&D), part of the mega-trend of scientization embedded within the ongoing rationalization of diverse spheres of life (Bromley & Meyer, 2015). France, Germany, and the UK maintain differentiated systems of universities that vary in size and prestige, yet all three host some of the strongest knowledge-producing organizations in the world. Whereas France and Germany have significant extra-university research institutes, connected in large umbrella associations or coordinated by government agencies, the UK relies most heavily on its internationalized research universities (Graf, 2009). The establishment and maintenance of research universities requires considerable investment: “The most consequential scientific revolutions of our time could not have happened in universities without massive government and/or corporate support” (Kennedy, 2015, p. 314), whether medical breakthroughs such as treatments for life-threatening illnesses or knowledge transmission infrastructures like the Internet.

Alongside the key indicator for the quantitative measurement of science (publications), institutional, personnel, or financial indicators likewise facilitate estimates of scientific growth and development. Rising science production demands commensurate resources (Weingart, 2001/2015), regardless of the actual, difficult-to-measure impact of any individual scientific article. While research on the relationship between R&D funding and demonstrated knowledge production is limited, studies confirm the general positive relationship between research funding and publication output (see Rosenbloom, Ginter, Juhl, & Heppert, 2014 on chemistry). Increasingly, research evaluation systems and competitive funding mechanisms determine the flows of resources. The UK, for example, distributes public funds for research on the basis of extensive peer review in the “Research Excellence Framework,” that many other countries seek to emulate.

First, we examine the inputs of these top science-producing countries, namely the “research intensity” measured as the gross domestic expenditures on R&D (GERD) as a proportion of GDP. This indicator across the countries shows considerable variance. In 2014, the OECD mean was 2.38% while the EU-15 mean was 2.09%. The UK, with rising absolute investments in R&D, reached only 1.70% GERD in 2014. France has been relatively stable above 2% since 2000 (2.26% in 2014), whereas Germany has increased its science investments to nearly 2.90%. Thus, none have fully reached the EU target of 3% to be invested in innovation – and these countries’ investments vary by a factor of almost two (Fig. 1).

While competition amongst the strongest science countries has risen in an age of self-proclaimed excellence, comparative indicators, and research evaluation systems, collaboration has also grown dramatically across cultures and countries (Zhang et al., 2015). Our selection of countries reflects HE and science systems with differently institutionalized structures, enabling us to

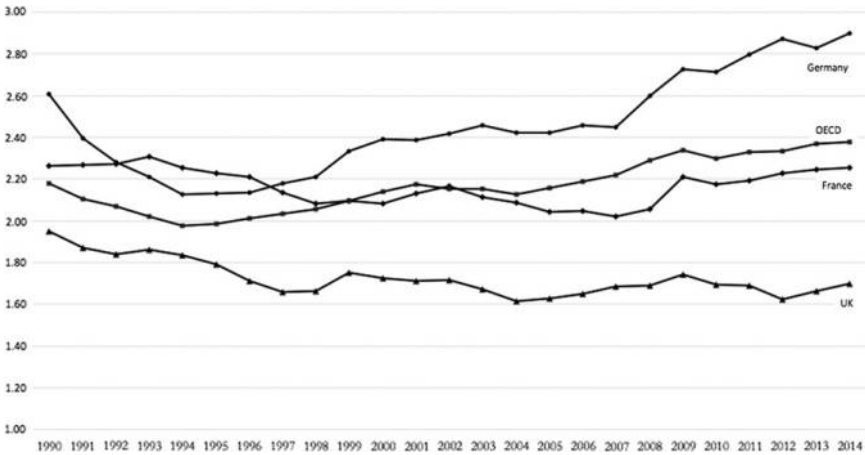


Fig. 1. Research Intensity in France, Germany, the United Kingdom, and OECD Average. GERD (as a proportion of GDP), 1990–2014. Source: OECD.stat. (2016): Main Science and Technology Indicators.

examine and compare, in the aggregate, those institutional setting(s) that provide favorable conditions for scientific productivity.

The institutional settings and organizational forms in which research is conducted affect overall capacity and scientific productivity. Establishing new organizations involves high costs and myriad challenges, with countries making challenging choices about which types of HE and research organizations will be most productive. State investment in science is often divided between universities and extra-university research institutes that have varying emphases (fundamental to applied) and with differing degrees of academic freedom. Research universities and institutes alike struggle to develop their reputations, which often requires generations of scholarship and exchange. Yet while research institutes may focus mainly on immediate scientific output, universities must balance research and teaching, the unity of which remains the foundational principle of the modern research university (Ash, 1999).

Universities receive around or less than a quarter of all R&D funds: only 18% in Germany, 21% in France, and 26% in the UK of the overall expenditures in R&D went to the HE sector (OECD.stat., 2016).¹ We might expect universities to produce proportionally more given their unique constellation of senior and junior academics across the disciplines. Alternatively, we might expect that research institutes selecting specialists in cutting-edge fields and devoted solely to research output will be more productive. This group of countries enables us to compare systems with varying constellations of science-producing organizational forms within diverse organizational fields – and varying importance of research universities within them.

While universities of all kinds experience “academic drift” and have many scientists intrinsically motivated to conduct research, universities in many countries are challenged by the lack of resources as many states retrench their commitments to public HE. This lack of support occurs even as the costs of tertiary education continuously rise (OECD, 2011). Increasing science budgets across Europe have, when calculated as a proportion of GDP, not kept pace with the rhetoric extolling the benefits of science and innovation (OECD, 2014). The rationale and vision shared by many governments of how to build capacity for science rests on the notion that infrastructure for research cannot be provided only by industry; that the state must invest in the so-called “knowledge triangle” – the beneficial combination of research activity, specialized education/training, and innovation that advances knowledge (European Commission, 2010, p. 3). Predictably, however, despite the state investments, HE and science systems and the resultant scientific productivity vary considerably across countries given long-term institutionalization (and intergenerational exchange) needed to build successful environments conducive to scientific discovery.

In Europe as elsewhere, the supranational dimension is becoming more influential, exemplified in intergovernmental processes leading to standardization in HE (Bologna process) and in such increasingly influential government initiatives (e.g., Horizon 2020, the EU’s framework program for science) and organizations (European Research Council) that fund European science on the frontier (Hoenig, 2017). While the UK has been globally successful far beyond its size, with a well-rounded and impactful research base, and was the most successful host country for scientists in receiving European funding, the “Brexit” vote in June 2016 to rescind membership in the European Union has already done damage to the standing of UK universities and research collaborations (de Freytas-Tamura, 2016). France and Germany, as two of the largest HE and science systems in Europe, show how important national state funding is in providing the necessary infrastructure for science production. Focusing on countries in the European center of science production, we compare growth over time in their HE and research systems and the resulting scientific productivity. We analyze the institutionalization of their systems – following different models and compositions of organizational forms and fields structured over centuries – and research policies, especially their investments in R&D.

Methodologically, we measure science production on the basis of data purchased from Thomson Reuters (Web of Science), which we supplemented through extensive archival research and recoding (see introduction to this volume). The database consists of a stratified representative sample of published papers in selected science and technology disciplines, including health (STEM+) from 1900 to 1970 and a complete database of all papers through 2010, although we focus on the most recent period of expansion from 1975 to 2010 here. The increasing role of conference proceedings in STEM+ disciplines with high growth rates (e.g., computer sciences and engineering) is only

partially reflected in the SCIE database. Nevertheless, peer-reviewed journal articles are the most important and traditional type of publications in these fields, next to patents – the growth rate of scientific publications is still increasing overall, with disciplinary differences (Olesen Larsen & von Ins, 2010). By including health-related disciplines, this dataset inflates somewhat the productivity of universities with academic teaching hospitals; however, medical research is genuine scientific output, furthermore with clear impact for society, a newer and stronger factor in research funding. Focusing on STEM+ disciplines, we examine research produced in universities and research institutes that rely heavily on public funds.² Selecting a set of disciplines is necessary, because disciplines form “the primary unit of internal differentiation of the modern system of science” (Stichweh, 1992, p. 4). While official publication figures under-represent the true extent of scientific production and SCIE data is biased toward the English language, nevertheless, peer-reviewed research articles indexed in the Web of Science or in Elsevier’s Scopus—as the two main databases—are the key source for most bibliometric analyses (Glänzel, 2016).

INSTITUTIONALIZING SCIENCE: RESEARCH UNIVERSITIES AND INSTITUTES

Theoretically, we apply a sociological neo-institutional framework to explore and explain both the tremendous expansion of HE and science across Europe and considerable differences across time and space in the institutional settings, organizational fields and forms, and organizations that produce the most research (Scott, 1995/2014, 2015). Science, as a social institution that follows internal social norms and rules (Merton, 1942), in turn provides the foundations for the production of scientific knowledge (Weingart, 2003/2013). As communities of organizations, organizational fields reflect the interrelationships of diverse organizations sharing an environment (Aldrich & Ruef, 1999). Within a field, particular organizational forms share similar functions and organizations by a common network; this is quite true within scientific communities that, spanning the globe, rely on familiar organizational forms, such as the university. Organizations are defined as social structures established to achieve specific goals through the coalition of actors embedded in an institutional environment (Scott, 1995/2014). The focus on the organizational field and organization levels enables an analysis of differential contributions to scientific productivity.

Universities with their institutional character are assumed to be the most appropriate organizational form for creating significant scientific knowledge, providing the setting for research simultaneously with teaching each new generation of scientists. Alongside universities, diverse state-supported research

institutes constitute another pillar of modern science. These various organizational forms undergird local, regional, and national economic development even as they expand human rights and individuals' capabilities (Meyer, 2009). Increasingly, individual well-being and societal futures rely on scientific discoveries, generated more than ever in research universities that remain key contributors of scientific outputs (Baker, 2014). Yet research institutes outside of universities constitute another crucial pillar of science. Despite numerous hypotheses regarding the transformation of knowledge production (Nowotny, Scott, & Gibbons, 2003), the variable contributions of different organizational forms across decades and in different countries have been rarely addressed in explicit comparisons (Zapp & Powell, 2017). We begin such exploratory analysis here, focusing on universities and research institutes as the primary organizational forms producing mainly state-funded research. Research universities are characterized by fundamental principles of the nexus of research and teaching, freedom to teach and to study, autonomy and commitment to science as well as the granting of doctoral degrees. In comparison, research institutes contribute less to teaching, instead focusing on research, often in well-resourced, cutting-edge, and specialized facilities.

These three countries differ in the scale and scope of their systems – and, as analyzed below – in the developmental pathways and distribution of their universities and research institutes. France, Germany, and the UK have centuries-old, world-renowned research universities. Both Germany and France also have well-established extra-university research institutes, often linked in extensive associations that contribute hugely to these countries' scientific output – and are world leaders (Oleksiyenko, 2014, p. 498). Especially in Germany and the UK, research universities are most significant organizations for producing science. In France, universities' research orientation has been strengthened over time, with research institutes and elite researchers producing STEM+ science in a range of organizational forms and, most recently, in research clusters (see Musselin, 2017).

According to the volume of produced STEM+ papers and to historical reach, we sketch the development of universities and research institutes in France, Germany, and the UK, showing how capacity for producing scientific papers has expanded. Europe has the oldest and leading universities worldwide such as the University of Oxford (teaching began around 1096), Paris-Sorbonne University (founded ca. 1150), or the University of Heidelberg (1386) that produce increasingly large numbers of publications and are globally interconnected. Research institutes – like those of France's *Centre national de la recherche scientifique* or Germany's Max Planck Society for the Advancement of Science – though founded in the 20th century, are similarly well-established. The countries differ in the time elapsed since establishment and in the differentiation of these organizational forms and fields. Comparing the three research university sectors, Germany and the UK are more highly institutionalized than

that in France. By contrast, in research institutes, France and Germany have large, differentiated non-university research sectors, whereas the UK does not.

We begin with process-tracing in each country, based on synthesis of the research literature in multiple languages and emphasizing the founding dates of organizations and system institutionalization. Process-tracing helps us to understand sequential (historical) events and allows us to explore developmental processes in specific cases (Mahoney, 2004, p. 88f.). We pair the historical case analysis with quantitative analysis of bibliometric data. This combination facilitates analysis of how these organizational forms and fields evolved and provides results on their scientific productivity.

FRANCE: ELITE PROFESSIONAL HIGHER EDUCATION AND RESEARCH BETWEEN HIERARCHY AND ACCESS ISSUES

France's differentiated HE system consists of a range of universities, some very strong in research and others focused more on teaching and applied fields. Universities are challenged by the elite higher professional schools, the *grandes écoles*, to attract talent. And in research the *Centre national de la recherche scientifique* (CNRS) is dominant, though many of its researchers establish or work in research "laboratories" (research groups) physically located within universities. France finances and maintains prestigious extra-university research units and institutes, many but not all under the CNRS umbrella. With 79 universities, 205 *grandes écoles*,³ and 14 foreign institutions, the professional school sector remains significant (METRIS, 2012). The Paris-Sorbonne University was among the first universities in Europe; for centuries the guarantor of academic excellence across diverse fields. Today's major concentration of universities in the capital city is built upon those ancient foundations. In 1970, shortly after the student protests of 1968, this institution was decentralized and divided into 13 autonomous universities (Musselin, 2007, p. 713). The national extra-university sector consists of seven larger umbrella research associations with more than 70 institutes, centers, or departments. Most recently, in what Musselin (2017) calls the "remodeling of French HE," consortia are being established to grow collaborations across organizational forms and aggregate research in stronger groupings of researchers and organizations. At Paris-Saclay, for example, bridges are being built between 18 research organizations, including two universities, an *Ecole Normale Supérieure*, six research organizations, ten engineering and business schools, and two educational clusters that host 10,000 researchers and 300 laboratories (organizational units of different size and structure).⁴ Clearly, the underlying theory is that physical proximity matters for scientific exchange; however, this does run counter to some

important features of the recent decades, namely globalization and intellectual exchange via virtual communication platforms.

Despite the principle of equivalence, France's tertiary education and research system exhibits stratification: the *grandes écoles*/university divide and the split between selective and non-selective segments as well as distinctions between CNRS researchers and academy members at the top and regular university faculty members below. While the key organizational form for research may be – increasingly – the university, CNRS laboratories and institutes play a key role within them and more generally in producing science (OECD, 2014). The *grandes écoles* constitute a diverse group of highly selective and prestigious institutions that train future elites: higher-level civil servants, professors and researchers, engineers, and company managers (Givord & Goux, 2007), but increasingly they also produce science. Widely criticized, this divide has often been blamed for the current crisis experienced by universities, as the *grandes écoles* attract high-achieving students and relegate universities to struggle for global reputation (Clark, 1995, p. 93). Thus, from 2006 “alliances” have been formed to join both organizational forms, such as in Centers for Research and Higher Education (PRES) (Le Deaut, 2013).

The contemporary university crisis also results from lack of resources, multiple incoherent reforms, lack of labor market forecasting, and increased bureaucratization (Bernhard, 2017). Universities' status is limited because neither are societal elites trained there nor are the most significant research projects initiated by them, thus they serve mainly as teaching bodies, even if some host influential research groups or laboratories. With notable exceptions and shifting recently, both *grandes écoles* and universities emphasize teaching more than they excel at research. The French HE system reflects an “education model,” emphasizing professional preparation (Kreckel, 2008, p. 88).

Yet French universities are changing, not least due to global norms and European standards. Universities were responsible for general education (except for law, medicine, and pharmacy), while *grandes écoles* offered vocational preparation of elites or middle-range technicians. Research was long conducted primarily in separate research organizations. A fundamental shift, the Liberties and Responsibilities of Universities (LRU) bill, passed in August 2007, grants significant power to university presidents. The proclaimed aim: to meet the demands of the “knowledge economy” and to bring French universities to the level of excellence of major international competitors. The French “excellence initiative,” designed to strengthen research collaborations and consortia of researchers within a differentiated HE system, cannot eliminate decades of specialization and uneven development. Ironically, the German Excellence Initiative aimed to do the opposite, creating more differentiation in a less stratified, less differentiated HE system (Müñch, 2007). Along with the diffusion of “performance discourse” and new instruments such as “agencification” came national calls designed to identify the best researchers and

encourage their collaboration; yet perhaps most significant is the requirement that all HEIs must be part of scientific consortia (Musselin, 2017).

Historically, some processes have successfully linked teaching and research in France. In the late 19th century, the new organizational form of *grands établissements* was established to support and develop education and research, including the *École pratique des hautes études* (1868) and the *Institut Pasteur* (1887), which has grown in capacity and influence (Hage & Mote, 2008). Founded in 1530, the *Collège de France* enjoys special status among the *grands établissements* (Kreckel, 2008).

Since 1939, fundamental research is predominantly financed by CNRS, the dominant association of research institutes, units, and laboratories. This state-funded, complex umbrella organization encompasses seven research institutes, three national institutes and 1,028 research units, with the vast majority (95%) joint laboratories with universities and industry. CNRS is significant for France's scientific development and international standing in a wide range of fields. Organized in associations, university faculty members may apply to establish collaborations with one of the national research institutes, or associated laboratories receive funding, and sometimes CNRS staff, while autonomous research units – called *unités propres* – have no university affiliation (Musselin & Vilkas, 1994, p. 129). The varying relationships of researchers to each other and the organizational forms in which they work confound analyses of affiliations and aggregate measurement of the impact of organizational conditions on outputs. Other publically funded extra-university research institutions conduct strategic research related to national needs, from infrastructure and energy to agriculture and health, all part of a powerful centralized state (Clark, 1995). The funding and organization of research has traditionally been the responsibility of separate organizations; with the institutional separation between HE and research difficult to bridge (Ben-David, 1977/1992, p. 107) – and continuously debated. Yet, this is precisely what French research policy seeks to accomplish today in establishing consortia connecting organizations and research groups. From 2009, the government's "Investments for the Future programs" aim to strengthen competitiveness through targeted investments in research, higher and vocational education, in particular enterprises, and in expanding sectors. Thus far, these programs have allocated €26.6 billion to HE and research (AFR, 2016). The traditional government-sponsored, largely autonomous research organizations operate alongside competitive project-based funding in large competitive programs (OECD, 2014). Thus, HE and research and development remain particularly complex in France, despite efforts are coordination and consolidation.

Turning now to output, we examine France's overall scientific productivity in STEM+. We find continuously rising output and strengthened university-based research. The non-university/university sectoral divide has been narrowed (Fig. 2). These sectors' output grew in parallel for decades, witnessing

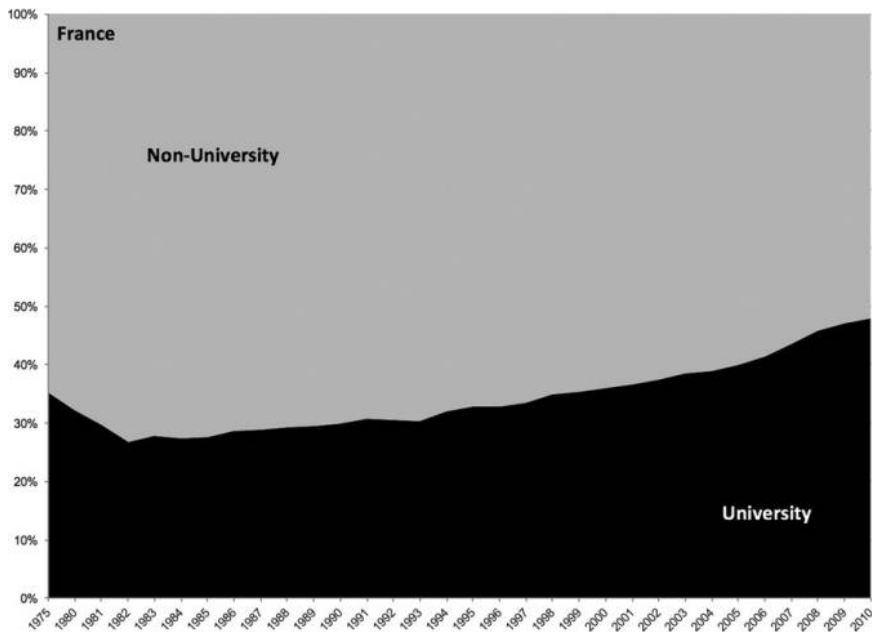


Fig. 2. Scientific Productivity in France: Universities versus Non-University Organizations, 1975–2010. Note: This representation is based on differentiating publications from organizations with the word “univ” from all others, thus is a rough measure of the productivity of the university versus non-university sector, which includes a range of science-producing organizations: firms, large government agencies, and academies. “Black” = university sector, “grey” = non-university sector. *Source:* SPHERE project database of SCIE publications (Thomson Reuters’ Web of Science).

considerable expansion from 2004 onward. Today, the two pillars of French science are at parity, at least in terms of STEM+ article publications.

In individual organizational terms, if we consider the diverse branches of the University of Paris together, the aggregated output of 15,453 articles clearly led this centralized country. The capital city’s university-based scientific output was produced by Paris VI Pierre and Marie Curie (4,714), Paris VII Diderot (3,165), Paris XI Sud (3,163) and Paris V Descartes (2,598). At a lower level of output were further branches, of Paris XII Est (1,036), Paris XIII Nord (392), and Paris IX Dauphine (135), with some authors listing their affiliations simply as University of Paris (undefined: 250).

By contrast, and unsurprisingly, the CNRS led the French research institute contribution in scientific productivity in 2010 with 6,497 research articles, collecting the intellectual products of the myriad research institutes, laboratories,

and individual scientists associated with France's leading scientific organization.

The University of Lyon – located in France's second largest city and consisting of 16 organizations, from universities to *grandes écoles* to research institutes (without counting the *École normale supérieure* there) – contributed 3,605 articles. Another southern university, Toulouse, was very productive (2,674), combining contributions from the two natural sciences branches Toulouse I Capitole and Toulouse III Paul Sabatier.

Three government agencies that contribute heavily in peer-reviewed scientific publications are the medical research institute *Institut national de la santé et de la recherche médicale* (INSERM) with 2,534 articles, the atomic energy commission (CEA) with 2,352, and the *Institut national de la recherche agronomique* (INRA) with 1,758. Further strong producers include the southern university, Provence Aix–Marseille I and III Paul Cezanne (campuses in both cities), which 2,339 pieces of scholarship. Grenoble Alpes University (here: Grenoble I Joseph Fournier) produced 1,886 and the University of Montpellier I and II contributed 1,861 articles in SCIE journals.

This list reflects two important particularities. First, that institutional affiliations in France tend to be multiple, with many CNRS researchers working within universities and universities collaborating with national research institutes. Second, universities have different branches for different fields, but the actual organizational setting in which the research was produced is not always distinguished. In bibliometric databases such as Thomson Reuters' Web of Science or Elsevier Scopus, the primary affiliation is paramount. A methodological challenge that qualitative research should address at the organizational level is how resources are provided within these settings and what reputational logics guide scientists in noting their affiliation(s).

Now we turn to Germany, a country with a similar duality of research universities (relatively similar in resources and reputations) and extra-university research institutes, albeit without the centralization characteristic of France.

GERMANY'S DUAL PILLARS OF STRENGTH: THE SYMBIOSIS OF RESEARCH UNIVERSITIES AND EXTRA-UNIVERSITY RESEARCH INSTITUTES

Germany is home of the undisputed model of the research university and significant extra-university research institutes. Yet universities have been underfunded for decades (Pritchard, 2006), despite considerable increases in the proportion of each cohort entering HE, and the sector is divided into two, with research universities and universities of applied sciences. Paradoxically, policy-makers have ignored this “institutional crisis” of underfunding HE even as they send ever more of their children into the system (Lenhardt, 2005): “Stagnation

of public funds is particularly damaging to efforts toward fostering internationally competitive basic research in the universities, as they receive only a relatively small share of the entire national research budget” (Baker, 2014, p. 93). Here, there is a decoupling between rhetoric and policy reality.

Indeed, the German “Humboldtian” model of university-based science is among the oldest and influential conceptions of HE worldwide (Humboldt, 1809), reaching mythic proportions, despite the ongoing transformation of German HE – not least reunification that led to unforeseen, dramatic dynamics in academia (Ash, 1999; Clark, 2006; Pritchard, 2006). While the foundational principle of the nexus of research and teaching enjoys sustained attention worldwide, the relationship remains complex and ambiguous both within organizations and between the organizational fields of HE and research. The success story of German research-based teaching relies on self-government, institutional and organizational growth, and its generality, dealing with matters of general human interest and preparing students for a broad range of occupations (Ben-David, 1977/1992).

Germany’s 126 research universities, 232 universities of applied sciences, and 51 art and music colleges operate alongside a research-intensive and powerful extra-university research institute sector of 300 institutes, most gathered in four large umbrella associations. With annual R&D investments among the highest in Europe (OECD, 2015), the Federal Ministry of Education and Research (BMBF) is the key actor in research policy, even as education is mostly the province of the *Länder*. Among public funding organizations, the German Research Foundation (DFG) is the main promoter of science as a peer-review organizing intermediary. Furthermore, the European Commission and more than 16,000 foundations offer innumerable possibilities to apply for financial support for education and research (Hinze, 2010).

Higher education devoted to research grew in Germany stronger than in more differentiated systems like that of France. This research-focused type of university continues to dominate German HE up to today, despite establishment of universities of applied sciences (*Fachhochschulen*) after massification of tertiary education. Since the 1960s, this new organizational form provides a more applied and praxis-oriented focus. Investments in (fundamental) research are less significant; however, increasingly their faculty members do conduct research, often collaborating with industry. Gradually, reflecting general trends of “academic drift,” they have become more like research universities, even if the monopoly on granting doctoral degrees remains in universities (Teichler, 2005).

Around WWI, Germany established an alliance between representatives of science, research-intensive industry, and ministerial bureaucrats to found innovative research institutes outside universities. The 1911 founding of the *Kaiser-Wilhelm-Gesellschaft* (from 1948 Max Planck Society) challenged the German HE system as the dominant locale for fundamental research. In this sector, research was institutionally separated from teaching. Today, 83 Max Planck

institutes are located in Germany and five institutes. After WWII, further competitors entered the growing organizational field of extra-university research: The Fraunhofer Society was established in 1949 to focus on applied sciences and industrial contract research (today: 67 institutes). The Leibniz Association was established in 1997, but had existed since 1977 known as the “blue list” (*Blaue Liste*), a collection of diverse research institutes with regional or national significance and varying emphases on fundamental or applied research (today: 89 institutes). The Helmholtz Association of German Research Centers (2001), dealing with research related to infrastructure (*Vorsorgeforschung*) comprises 18 very large research institutions (*Großforschungseinrichtungen*) and around 40 federal research institutions in a range of fields related to national interests (Hohn, 2010). Yet all of these research institutes and their umbrella associations continue to rely on universities for crucial aspects of their work, whether it be training of young scholars or certifying doctoral candidates. Thus, the competition must be considered more of a symbiosis, with elements of collaboration and competition continuously (re)negotiated.

Universities have come under threat due to declining funds and internationalization and Europeanization processes. Competition between universities and research institutes has increased as centers of excellent research outside universities intensify their activities, increase investment in cutting-edge research projects, and amass the best and brightest scientists. Their enviable funding derives from both Federal and *Länder* governments jointly providing funding, though in differing proportion (usually 50/50) (Hohn, 2010). Germany’s dual pillars of mass universities and independent research institutes continue to boast prodigious scientific output – and the universities’ central position has been maintained.

With the emergence of newer hybrid types of research (and teaching) as well as universities of applied science demanding the right to confer doctoral degrees, the German HE system confronts a new situation. The structural duality of the German system no longer seems unassailable or as sustainable. Examples of newer boundary-spanning organizations include the Karlsruhe Institute of Technology (KIT), an amalgam of the Karlsruhe Research Center (Helmholtz) and the Technical University of Karlsruhe, as well as the International Max Planck Research Schools (IMPRS) as examples for inter-institutional, international, and interdisciplinary collaboration (www.mpg.de/de/imprs). Because only research universities in Germany have granted doctoral degrees, others depend on close collaboration or “strategic partnerships.” Furthermore, such collaborations have also been affected by three developments: massification, segregation of research and teaching, and growing third-party funded research.

Turning now to our examination of Germany’s SCIE scientific output over the past several decades, we unsurprisingly find dual pillars of strength in science, with ultrastability in the university/non-university distribution, with about 60% of all STEM+ publications having at least one university-based author

(Fig. 3). Symbiosis of research institutes and research universities viewed in explicit collaborations is particularly strong in doctoral education and the conferral of doctoral degrees, for which the institutes have been wholly dependent on universities.

The Max Planck Society, with its dozens of institutes and emphasis on fundamental research, produced 6,374 research articles, with a further 225 more generally ascribed to the Max Planck Society itself. Among the leading 37 MPIs are those researching Astrophysics, Extraterrestrial Physics, Solid State, Polymers, Astronomics, Biogeochemistry, Colloids and Interfaces, Radioastronomy, Nuclear Physics, Biophysical Chemistry, Physics of Complex Systems (all above 200 contributions in 2010).

The researchers in the large Helmholtz Association institutes together published 4,556 papers in 2010, with the leading organizations being the Jülich Research Center (871), the German Cancer Research Center Heidelberg (829),

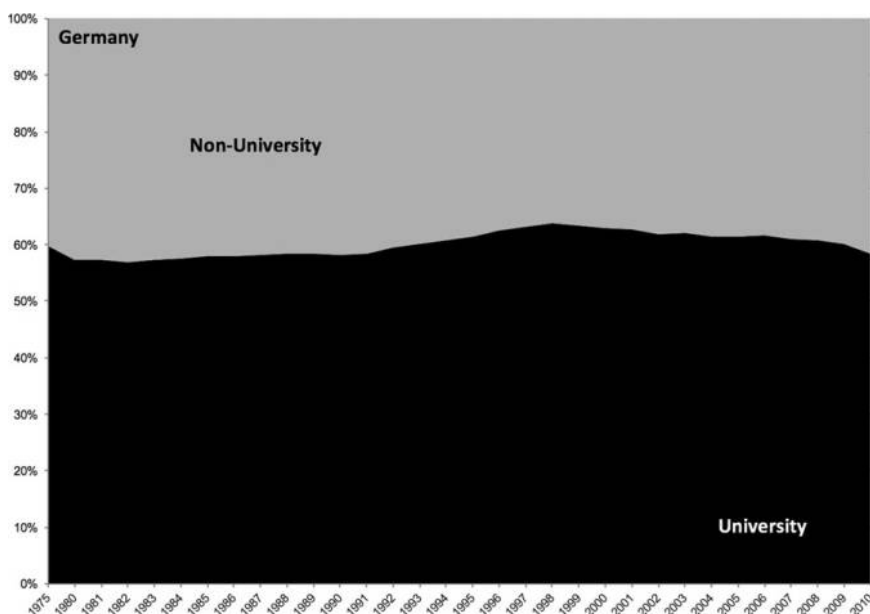


Fig. 3. Scientific Productivity in Germany: Universities versus Non-University Organizations, 1975–2010. *Note:* This representation is based on differentiating publications from organizations with the word “univ” from all others, thus is a rough measure of the productivity of the university versus non-university sector, which includes a range of science-producing organizations: firms, large government agencies, and academies (e.g., in the GDR). “Black” = university sector, “grey” = non-university sector. *Source:* SPHERE project database of SCIE publications (Thomson Reuters’ Web of Science).

Helmholtz Center Munich (460), Polar and Ocean Research Alfred Wegener (348), Environmental Research (310), German Electron Synchrotron (DESY) (290), Materials and Energy (208), and Max Delbrück Center for Molecular Medicine (206), along with several others under 200 contributions each.

The top three universities in the STEM+ fields are LMU Munich with 2,977; University of Heidelberg with 2,976; and the Technical University Munich with 2,712. Berlin's 300-year-old medical research and teaching center, the Charité – Universitätsmedizin Berlin which collaborates intensively with the universities in Berlin with medical faculties, produced 2,030 in 2010. Indeed, we find that medical research contributes considerably to many of the universities' output, with those universities with medical faculties producing significantly more STEM+ research, due to the publication intensity of medical fields. These include the University Erlangen-Nuremberg (1,956), the University of Freiburg (1,951), University of Tübingen (1,865), and the University of Bonn (1,827).

Thus, in both France and Germany, extra-university research institutes play an important role in research, as do the associations that directly fund research by selecting the best scientists and providing them with research-conducive conditions. The continued strength of Germany's two main pillars of research capacity mirror France's structural duality. Despite the dual structure that places emphasis and concentrates resources in the research institutes, with varying degrees of independence and collaborations across the institutional divide, both enjoy significant capacity and output.

We now turn to the UK, in which a strong and internationalized organizational field of universities contributes disproportionately to global scientific output.

UNITED KINGDOM: FROM UNDERGRADUATE COLLEGES TO LEADING INTERNATIONAL RESEARCH UNIVERSITIES

The UK enjoys a leading position in global science, as it is home to ancient learned societies, such as The Royal Society (founded 1660), and it continues to contribute far more than its size would suggest: although representing less than 1% of the world's population, it expends 3.2% of global R&D, and hosts 4.1% of the world's researchers (Elsevier, 2013). Like those of France and Germany, the history of HE in the UK begins many centuries ago; it is home to some of the world's oldest and most-renowned universities. With teaching in the city of Oxford documented as early as 1096, the University of Oxford can be considered the oldest university in the English-speaking world. Similarly, the University of Cambridge celebrated its 800th anniversary in 2009, charting its existence back to an association of scholars who gathered there in 1209. In Scotland, St Andrews, Glasgow, and Aberdeen were established in the 15th

century, with the University of Edinburgh founded by royal charter in 1583. A first major expansion of HE occurred in the 19th century with further royal charters awarded to St David's College in Lampeter (1822; later becoming part of the University of Wales), Durham University, King's College London, and University College London. In Northern Ireland, Queen's University Belfast, which has its roots in the Belfast Academical Institution (founded 1810), is also among the UK's oldest universities. These institutions of higher learning in the UK continue to be recognized as leading universities not only in the English-speaking world.

The British model of HE reflects a system originally supporting classical education for a very select few to become "educated gentlemen" of the ruling class (Cummings, 1999, p. 424). Thus, as in France, the original target group was a tiny elite, many of whom had previously attended college preparatory boarding schools. These young men were provided a classical learning canon in the colleges of Cambridge and Oxford. These exemplary HE organizations became an attractive model around the world, in all the Commonwealth countries and in the United States (Powell et al., 2012).

The traditional images of British HE are, however, far removed from the system's contemporary reality, with the original colleges now part of a differentiated HE system educating a large minority of each cohort. While the autonomy of HEIs was long guaranteed under state guardianship, with governance decentralized, more recently emphases on markets (and quickly and considerably rising tuition fees) and individual responsibility have increased. The state has massively retrenched its support for HE, leading to privatization and marketization. Evidence of loose coupling between the rhetorics of Europeanization and the structures of education systems, UK HE has been active in the Bologna process from the start – with limited impact in the aims or practices of individual universities, many already operating very successfully internationally (Graf, 2009), including large proportions of (fee-paying) international students and international branch campuses. Currently, the planned exit of Britain from the EU poses a major further threat to the system. While the HE system in the UK includes prestigious institutions of higher learning, it also integrates dozens of universities, especially the former polytechnics, that remain oriented far more toward undergraduate education instead of research, similar to the French universities.

Originally, medical, science, and engineering colleges were founded across England in major industrial cities. Eventually, these colleges would be transformed into the so-called red-brick universities in cities such as Birmingham, Bristol, Leeds, Liverpool, Manchester, and Sheffield. The post-WWII period witnessed tremendous HE expansion responding to the demands of a growing population and supposedly to meet the needs of an increasingly technological economy. Governments expanded the HE sector by establishing new colleges of advanced technology, which were later awarded university status in the 1960s such as Aston, Bath, Bradford, Brunel, City, Loughborough, Salford, and

Surrey. In Wales, the University of Wales Institute of Science and Technology became a constituent part of today's Cardiff University. The academic drift and rebranding did not stop there. The former university colleges (Hull, Leicester) were granted university status and seven new universities – East Anglia, Essex, Kent, Lancaster, Sussex, Warwick, and York – were founded.

A further, most significant round of expansion occurred in 1992 with the *Further and Higher Education Act*, in which the UK government granted university status to 35 former polytechnics and other organizational forms, mainly colleges of higher and further education. In formally abolishing the binary divide between universities and polytechnics and fostering a unitary HE system, the number of universities almost doubled and the number of university students doubled virtually overnight (Halsey, 2000, cited in Boliver, 2015, p. 608). If in 1984 there were 48 HEIs with university status, after the policy reform in 1992 (the *Further and Higher Education Act*), the number rose to 86 (Tight, 2009). Finally, in the new century, several dozen additional universities were created. Collectively, these universities are referred to as “post-92” or “modern” universities, many building on extended histories as vocational training organizations.

A number of classifications of HEIs in the UK exist, including the self-selected association of 24 public research universities called the “Russell Group” since 1994. Three other associations, mainly representing post-1992 universities are (1) the “Million+” Association for Modern Universities since 1997 (originally the Coalition of Modern Universities that seeks to widen access to HE among its 17 members); (2) GuildHE, since 2006 representing 28 “smaller and specialist” post-1992 universities and university colleges; and (3) the University Alliance, since 2006, of 20 post-1992 and two Robbins-era universities with a science and technology focus (Boliver, 2015). Given its predominance in research, the Russell Group association views its mission as “supporting the nation’s world-class universities and a diverse HE system [that] will help ensure the UK continues to enjoy the international recognition it rightly deserves for the quality of its educational provision and cutting-edge research” (Russell Group, 2012). Established in 1994, it represents members’ interests, principally to government and parliament, of the most research-oriented UK universities that together receive around two-thirds of all university research grant and contract income in the UK, award the majority of doctorates, and serve around a third of all students studying in the UK from outside the EU.

In research funding, the UK has what is probably the most influential system worldwide, currently named the Research Excellence Framework, started in 1986: confirming its ever-stronger presence in UK HE, seven assessment exercises have been conducted, leading to selectivity in which scholars’ work is evaluated and heightened stratification in HE. Other countries have begun to develop similar research evaluation systems to evaluate the quality of research and (re)allocate government funding for research. Such evaluations are related

to “excellence initiatives” both France and Germany used to distribute research funds to the strongest universities or their organizational subunits – based on submitted proposals that undergo extensive peer review. These various programs attempt to promote and achieve “excellence” in research, to produce innovative knowledge, and develop technology for the advancement of economy and society.

In terms of the sectoral sources of total SCIE scientific output since 1975, the universities have even increased, from half to two-thirds of all STEM+ publications with a university-based author (Fig. 4).

In this university-dominated research system, with differentiation in the HE sector, it is important to distinguish groups of universities. In 2015/2016, following the latest research evaluation – 2014 REF – the 19 English universities with research funding allocations in excess of £20m (excluding transitional

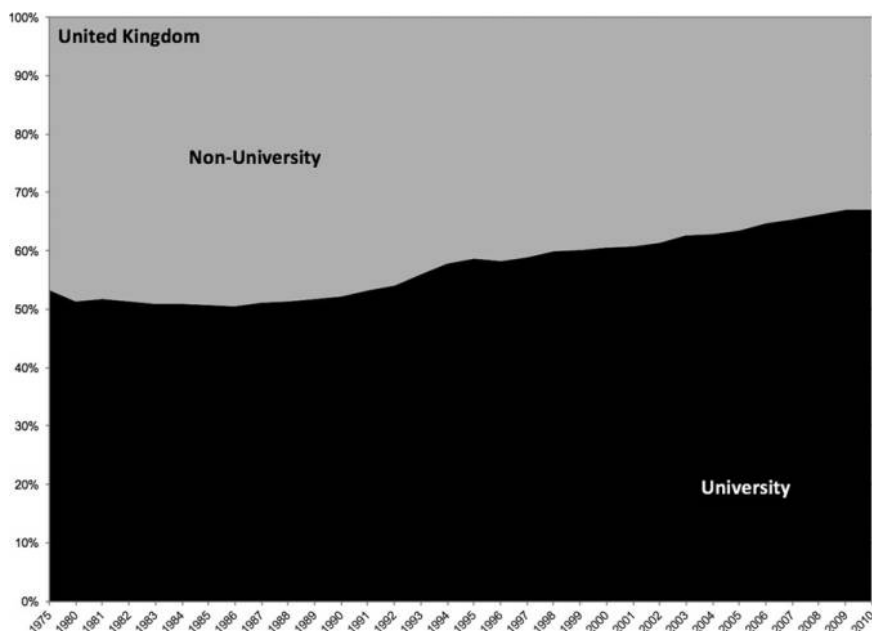


Fig. 4. Scientific Productivity in France, Germany, and the United Kingdom: Universities versus Non-University Organizations, 1975–2010. *Note:* This representation is based on differentiating publications from organizations with the word “univ” from all others, thus is a rough measure of the productivity of the university versus non-university sector, which includes a range of science-producing organizations: firms, large government agencies, and academies. “Black” = university sector, “grey” = non-university sector. *Source:* SPHERE project database of SCIE publications (Thomson Reuters’ Web of Science).

funding) from the Higher Education Funding Councils (e.g., HEFC for England) were all members of the Russell Group. These universities together received four-fifths of the total HEFCE research funding allocation, emphasizing the concentration of research funding from the state among a small group of research universities. Examining the UK's SCIE scientific output in 2010, the Russell Group universities are the foundation for research in England. Boliver (2015) argues that Oxford and Cambridge remain distinct in their research intensity and publication output as individual organizations. Yet our results show that the associated colleges and universities of the University of London have a higher combined output of STEM+ research articles, with a total of 13,125, led by the most prolific university in our sample, namely University College London (UCL) with 5,596. Further London-based top producers include the second-ranked Imperial College (5,292); King's College London (2,868); Queen Mary (1,069); and London School of Hygiene and Tropical Medicine (946); among others. The University of Oxford contributed 5,161 and the University of Cambridge 4,854. Manchester produced 3,188 papers; Bristol 2,396; Nottingham 2,204; Leeds 2,201; Birmingham 2,174; and Southampton 2,033, showing a relatively even distribution among top research universities beyond London and Oxbridge.

No single government agency, research institute or firm in the UK can match the research output measured in peer-reviewed articles in academic journals of the universities, an interesting contrast to the other two countries analyzed here. We now turn to explicit comparison of the three cases.

COMPARING COUNTRIES' STRUCTURES AND SCIENTIFIC PRODUCTIVITY: FINDINGS AND OUTLOOK

The over time and cross-national comparisons emphasize that France, Germany, and the UK have varying research intensity and proportions of scientists of all employees. Their HE and research systems reflect varying involvement of the state and particular institutionalization pathways that have resulted in the differing significance of research universities and institutes, each organizational form contributing more or less to scientific productivity. In these countries, research universities and research institutes (often gathered in umbrella associations) contribute different proportions to overall scientific output, yet in all three the research university represents the key organizational form – even growing in significance over time.

We compare the scientific productivity in France, Germany, and the UK over the past three and half decades, beginning with the input-side of investments (GERD). We then turn to per capita indicators of output before examining the organizational forms that produce this science, emphasizing the

distinction between the relative contributions of universities and non-university organizations. The latter category includes research institutes, government agencies, companies, and other research producers.

As mentioned above, in R&D spending per capita, Germany spent by far the most, followed by France, and the UK trailing behind. Cole and Phelan (1999) have argued that wealth strongly, but not completely, influences the volume of research produced by countries. Indeed, the number of researchers per thousand in the labor force in these countries does not vary markedly, from 8.2 in Germany to 8.9 in the UK to 9.9 in France (OECD, 2016). Differences between these three prosperous European countries in scientific productivity cannot be fully explained by differences of overall investments or the volume of researchers engaged in science. Rather, the institutionalization and distribution of organizational forms in which researchers produce science remain crucial factors to be examined further as are disciplinary emphases.

In contrast to these investments, in terms of outputs, measured here in SCIE publications per million inhabitants, the UK has the highest productivity, followed by Germany, and then France. All three countries witnessed continuously and steadily rising publication output per million inhabitants. Resources fully explain neither the expansion nor the country-level differences found. With targeted investments and much larger proportion of GDP going to R&D than the other two countries, Germany recovered from the shock of reunification. In fact, Germany's steady upward trend contrasts with a slight lowering of output per million inhabitants in 2005 in France and the UK, with Germany now slightly ahead of France. In 2010, France produced 856 SCIE articles per million inhabitants, Germany 908, and the UK 1,129. In the UK, factors such as the hegemonic language of English, international research collaborations, and the strong research-oriented universities factor in this surprising result given the lower level of research investment.

Analyzing the total number of SCIE publications for the three countries over the 20th century shows massive increases, especially since the 1970s and again over the past decade. With differences in scale, France, Germany, and the UK have all increased their output dramatically over the past four decades. As absolute numbers are difficult to interpret across cases of different size and science capacity, we calculated the scientific output per one million inhabitants (Fig. 5). This enables a more reliable comparative measure of the productivity based on SCIE publications in leading journals. While the long-term scientific strength of Germany (even during the division of West and East Germany) continues to the present day, it is the UK, with its highly internationalized and Anglophone research universities, that leads in per capita productivity, followed by Germany and France, although these two continental systems have had relatively similar production per capita throughout the period, with a similar, but slightly lower trend as that seen in the UK.



Fig. 5. Number of Publications from France, Germany, and the United Kingdom (per million inhabitants), 1975–2010. *Source:* SPHERE project database of SCIE publications (Thomson Reuters' Web of Science).

Comparing the absolute productivity levels of countries historically manifests the dramatic rise of science. The three countries examined here have, since the 1980s, witnessed a veritable boom in the publication of scientific articles in STEM+ disciplines. Comparing cases, we must acknowledge issues of scale and scope. When analyzing the number of these publications standardized by population, we find an even more dramatic rise, especially over the past decade. This provides a more comparable indicator and also reorders the countries in terms of productivity.

Our study investigated the contributions of different research organizational forms to scientific output. We compared the production of STEM+ research papers in three countries in Europe since 1975. As discussed earlier, these countries achieve their scientific outputs having distinct and differently institutionalized HE and science systems, yet with the universities at the core in all countries (see also other country studies in this volume). Germany and the UK have long-established research universities that produce a large number of articles – more than do the equivalent organizations in aggregate in France. France, while relying on a group of strong universities, emphasizes teaching and has fewer such organizations than does Germany. But, France also funds a diversity of well-established research institutes and other organizational forms such as the researchers and laboratories of the influential and highly productive CNRS. Still, France follows Germany slightly in the total number of publications.

Our key finding is that the institutionalization of the research university sector and reliance on it seems to support high productivity. In fact, those large and dual structured systems with a larger institutionalized non-university sector, as in France and Germany, have less per capita output than the UK with its group of world-leading universities that has attracted top talent globally. From 1975 to 2011, we see stable (Germany) or rising university contributions (France, UK) (Figs. 2–4). France initially had a very low university contribution (around 30%), but that this has risen over the past decades. In the UK, the growth of university-produced science went from around half to just under 70%. By contrast, we find stability around 60% in Germany, despite the enormous growth of HE and the dual structure of universities (and universities of applied science) and the strong, elite research institutes.

Examining the three top contributors to the European center of science productivity, we found remarkable sustained growth, building on the evolving institutionalization of research universities and institutes and embeddedness in worldwide scientific networks. The elaboration and technology-driven expansion of scientific communication through a world of scientific journals built upon peer-review and rising (inter)national competition and collaboration in STEM+ fields spur global growth – with Europe still central to global science. Although in the past Germany and France were outpaced by the UK, it is questionable whether the country can maintain its high standard and extraordinary success in international collaborations post-Brexit, as scientists declared in a *Nature* (2016) poll.

Simply more investment in R&D does not necessarily yield more STEM+ research in international, mainly English language journals indexed by Thomson Reuters' Web of Science database, although its coverage is steadily growing. In analyzing what makes these European countries successful in science, but to varying degrees, we identified the long-term development yet differential elaboration of research universities and research institutes. Internationalization and the global *lingua franca* of English in which research must be reported in leading SCIE journals changes the attention paid to particular research or the measurement of productivity; more generally it shifts the conditions of the research enterprise and the publication strategies of individual researchers. These factors require further fine-grained analysis. Next steps in understanding better the publication patterns in the STEM+ fields include analysis of the contributions of various organizational forms in the diverse non-university sector and organization-level studies of the most productive organizations identified here.

In cross-national and historical comparison, neither solely size of country nor level of R&D investments account completely for the growth of scientific production and productivity. Newer entrants to the world of science can quickly increase their capacity and productivity by investing heavily in research infrastructure and recruiting talent worldwide (see the example of Qatar; Crist, 2017). Yet especially the older established universities and associations of

research institutes have successfully driven the considerable increase in science production over the past several decades. The exploratory historical and comparative research reported here uncovered huge growth over time, due to academic drift, technology-facilitated communication, and collaborations. We also find relatively stable patterns of productivity of the universities within countries. In contrast to Germany's ultrastability, there has been strong growth in France and increases in the UK on an already high level from the mid-1970s. The center of science today reflects the strengthening of research in European universities, with France, Germany, and the UK contributing significantly to global science.

NOTES

1. OECD Main Science & Technology Indicators. Accessed on August 14, 2016.
2. We cannot here address in-depth ancillary questions of disciplinary differentiation, industrial investment in R&D or the fluctuating influence of academies of science.
3. Disagreement persists about the number of *grandes écoles*. The *Conférence des Grandes Ecoles* notes 205 *grandes écoles* in France (<http://www.cge.asso.fr/en/our-members/grandes-ecoles>).
4. <https://www.universite-paris-saclay.fr/en>

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