Global Research Report
U.S. research trends: The impact of globalization and collaboration

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Cover image: A detailed interior view of the U.S. Capitol Building dome, Washington DC

Executive summary

This Global Research Report examines the trajectory of recent United States research, focuses on the balance of domestic and collaborative research and its policy implications, including the redistributive effects of the Established Program to Stimulate Competitive Research (EPSCoR), and raises questions as to how well past investment has prepared the U.S. scientific enterprise to achieve its specified goals.

Key findings:

Capacity: Research investment (Figure 1), domestic research student numbers and the output of research articles and reviews (Figure 2) have not grown at the same rate as other parts of the world and the U.S. is faced with increasing competition from new science-based economies in Asia as well as an expanded EU network.

Portfolio: The U.S. 'footprint' in research remains extensive and diverse (Figure 3) but its research subject diversity has declined because the science budget expanded much faster in biomedicine than in technology areas (Figure 4), while other countries/regions have diversified and grown to challenge its historical strengths.

Impact: The U.S. is strong but no longer dominates the research landscape as it did, sharing this on an increasingly equal basis with other G7 nations and at close to eye level with Mainland China. Profile analyses reveal that more U.S. papers are now of world average citation impact (an indicator of utility, influence and significance) while competitors are producing relatively more papers of the highest citation impact (Figure 5).

Collaboration: International research collaboration has expanded pervasively across the globe. Most growth in U.S. research output is attributable to collaboration (Figure 6), doubling for major traditional partners such as the United Kingdom and Germany and quadrupling with Mainland China (Table 1). The citation impact of collaborative papers is greater than domestic research and has mitigated a decline in overall U.S. impact indicators (Figure 7).

Balance: U.S. research collaboration is greatest in the physical sciences and in technology subjects (Figure 8). It accounts for over 50% of output in most science/engineering areas and includes a diverse network of partners. Mainland China is the most frequent partner in technology research and is as frequent as the U.K. and Germany in physical sciences (Figure 9).

Geographical diversity: In common with other post-industrial economies, the U.S. has sought to address over-concentration of its innovation and development resources by structured funding directed to areas of relatively weak research capacity (Table 2). The evidence indicates there has been a shift to greater equity in the distribution of excellence through rising impact in U.S. states of historically low research output (Figure 10).

Conclusions: The U.S. remains a leading science and technology power but unless it acknowledges and addresses its shrinking domestic research capacity and works pragmatically with resourceful competitors such as Mainland China, it risks falling behind new science-based economies in Asia.

Mainland China is the U.S.'s most frequent collaboration partner in technology research.

Introduction

Globalization and increased competition, from rapidly developing nations such as Brazil, India, South Korea and especially from Mainland China, now characterize a different geography of research.

The U.S. has been a dominant force in global science due to its size, sustained investment in research and development and high quality educational system since the publication of Vannevar Bush's influential and widely respected report, *Science - the Endless Frontier,* at the end of World War II. In the 21st century, however, the U.S. finds itself in a changing environment. Globalization and increased competition, from rapidly developing nations such as Brazil, India, South Korea and especially from Mainland China, now characterize a different geography of research.

We first reported in detail on the state of the U.S. research base in 2010 (Adams and Pendlebury, 2010). Our data at that time showed that U.S. scientific research remained strong, but we also echoed concerns raised in *Rising Above the Gathering Storm*, the U.S. National Academies 2007 report. The U.S. was depicted as a possibly over-mature scientific enterprise: "Nations, like people, are freer to sketch and plan when institutions have yet to be built and resources are still uncommitted than at a later stage when the die has been cast and one must live with what one has chosen" (Finley, 1966). The U.S. had 'the die' whereas developing nations such as Mainland China, Singapore and South Korea were fashioning bold plans for the future. These nations were increasing their investments in research as a percentage of GDP from a relatively modest base and competition could only increase. In Europe, separate countries were increasingly engaged collectively in developing a European Research Area that drew on the collaborative capacity across nations, shared resources and a diversity of ideas and opportunities. Competition was growing then and now we can point to Argentina, Ethiopia, Indonesia and Vietnam as even newer but rapidly rising members of the global research network.

The die had been cast not only in terms of scientific enterprise but more comprehensively across the economy. U.S. success had been built upon U.S. industrial competence and productivity. But the heavy industries like coal and steel were being succeeded by new biomedical and information technologies into which emerging nations could move directly. Meanwhile the older G7 economies had to address the impact of post-industrial shifts in economic geography and workforce skills.

This report amplifies and strengthens the concerns expressed more than a decade ago. First, we detect signs that the U.S. research base is no longer pulling the rest of the global research system in its wake. It has become more concentrated than some other systems. It has been losing share of world outputs in the face of growing global competition. Meanwhile the increasingly successful European regional network (the EU-27, after the U.K.'s departure) has both maintained its share and enabled individual countries to improve their comparative international research performance. Second, U.S. research is both being challenged by, and increasingly sharing an agenda and a substantive portion of research outcomes with Mainland China. Mainland China also has become its most frequent partner, co-authoring one academic research paper in every 10 published with a U.S. research address and around one-third of U.S. engineering and technology research publications.

On August 30, 2019, Russell Vought (Acting Director, U.S. Office of Management and Budget) and Kelvin T. Droegemeier (Director, U.S. Office of Science and Technology Policy [OSTP]) issued a memorandum from the Executive Office of the President on the R&D budget priorities for FY2021. That note set out a series of priorities for technologies expected to power "Industries of the Future" and argued: "Sustained, strategic R&D investment in these emerging technologies and the materials, manufacturing, and computing that support them will advance American S&T [science and technology] leadership in the short term and catalyze discoveries and innovations that will shape the global S&T landscape." Leading topics named in the memorandum included: artificial intelligence, quantum science and computing, advanced communications networks and advanced manufacturing. Other areas named were: energy, oceans, earth systems, biomedicine and the bioeconomy. Since then, the U.S. Congress has taken action resulting in the CHIPS Act of 2022 which includes several proposals to respond to Mainland China's growing strength in science and technology. The Biden administration has also focused on research security in an effort to reduce the likelihood of technology transfer to U.S. competitors. Despite such efforts, this report will show that rapidly increasing collaboration with Mainland China is in fact intense in areas critical to U.S. Administration strategy.

For example, U.S. research output linked to semiconductors has stagnated at around 2,500 to 3,000 articles and reviews each year since 2005 while world output more than doubled from less than 10,000 to nearly 20,000 papers. Fewer than 12% of semiconductors are now manufactured in the U.S., down from approximately 37% in the 1990s. To address this, the CHIPS Act of 2022 provides incentives and subsidies for domestic manufacturing of semiconductors, including advanced chips that are critical for U.S. national security. In addition to enhancing competitiveness, the CHIPS Act also promotes translational research to hasten the conversion of basic research into marketable products and to address societal and economic challenges. There is also funding for enhancing geographical and stakeholder diversity to broaden participation in the research and innovation enterprise.

Rapidly increasing collaboration with Mainland China is intense in areas critical to U.S. Administration strategy.

Research capacity

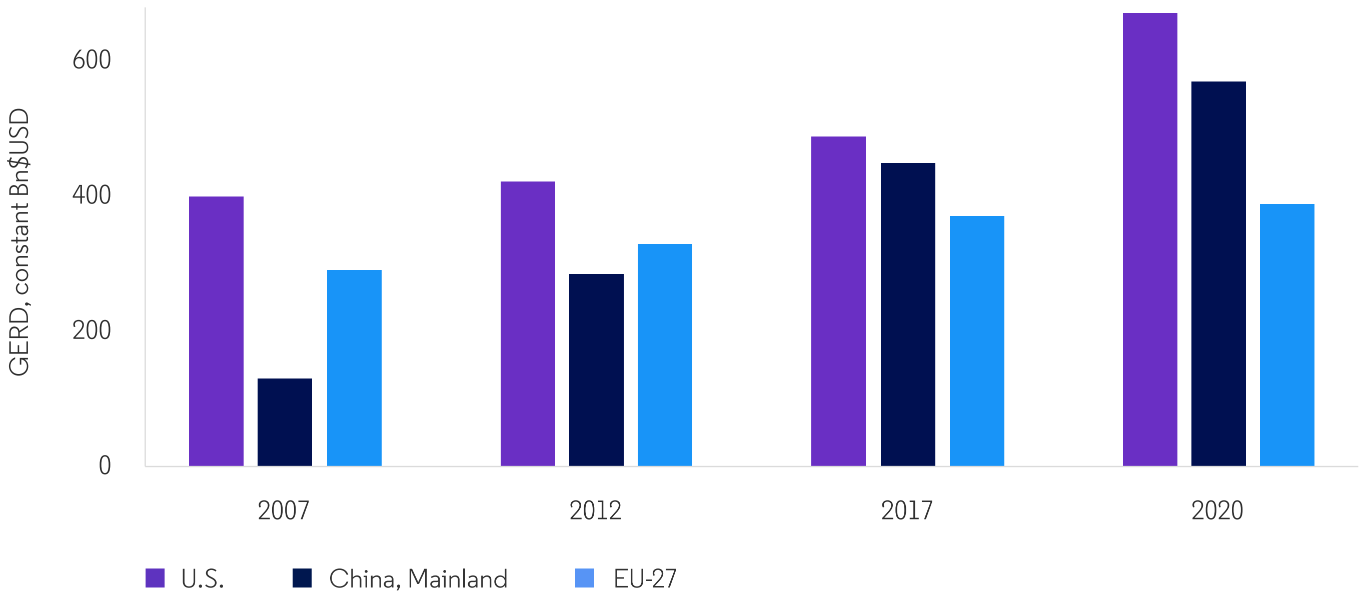
Research investment (Figure 1), domestic research student numbers and the output of research articles and reviews (Figure 2) have not grown at the same rate as other parts of the world and the U.S. is faced with increasing competition from new science-based economies in Asia as well as an expanded EU network.

The most dramatic development in the global research landscape over the last half century has been the rise in research contributed by Asia-Pacific countries/regions.

R&D investment for Asian countries/regions as a group surpassed the U.S. in 2008. In 2007, Asia's Gross Expenditure on Research and Development (GERD, here indexed via OECD data for 2010 U.S. dollars adjusted for Purchasing Power Parity) was $387 billion while that of the U.S. was $395 billion and the comparable figure for the European Union (then the EU-28) was $288 billion. By 2012, Mainland China alone had more than doubled its GERD compared to 2007 to $281 billion and South Korea had increased its spend from $40 billion to $65 billion, which was 4% of GDP compared to the U.S. at 2.7% of GDP. OECD data for 2020 show Mainland China at $564 billion on the heels of the U.S. at $633 billion, with South Korea at $103 billion (4.8% GDP) while the EU-27 has reached an average of 2.2% GDP but only $384 billion. Mainland China's research investment draws on only 2.4% of its GDP so it appears to have financial capacity in reserve and while the OECD suggested that a smaller increase in 2017/2018 might signal a slowdown in R&D investment, the subsequent outturn maintained its trajectory (Figure 1).

Research capacity requires trained people. As *Rising Above the Gathering Storm* noted, the U.S. research enterprise has become increasingly dependent on overseas postgraduate and postdoctoral recruitment to sustain its demand for high-level talent. OECD data for 2017 showed that more than 800,000 international students pursued an advanced degree or postdoctoral training in the U.S., of whom about one-third were Chinese. Back in 1995 there were similar numbers of U.S. and international full-time graduate students in computer science but in the following 20 years the number of international students increased 10 times faster than the U.S. domestic student population. The National Science Foundation's Survey of Doctorate Recipients (NSF, 2017) reported that international students represented 35% of graduate students throughout the science, health and engineering fields. The top three countries/regions earning U.S. PhDs were Mainland China, India and South Korea respectively, accounting for 54%

Figure 1.
Gross Expenditure on Research and Development (GERD). All figures in constant 2010 USD and adjusted for Purchasing Power Parity (source: OECD MSTI 2021).



of total non-U.S. doctoral graduates. The data show that domestic students in electrical engineering decreased in numbers over the last decade while the number of international students increased three-fold to represent 80% of the researcher population.

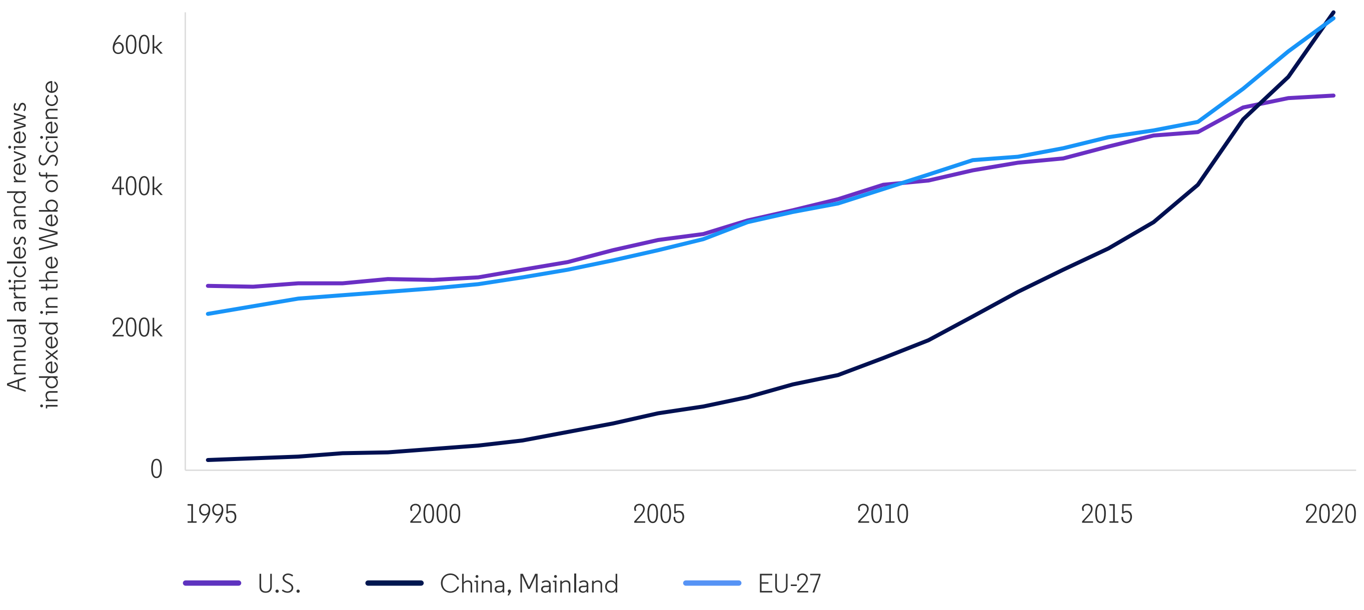
The U.S. share of indexed world literature is decreasing. Four decades ago, U.S. scientists fielded nearly 40% of the articles and reviews in the journals indexed in the Web of Science, a database that represents a cross-section of the leading international research literature, carefully selected and maintained to constant and well-publicized standards. The Web of Science has seen some re-balancing of journal coverage in recent years to respond to the changes in Asia and elsewhere. Currently, the indexed share of the world literature that carries the address of a U.S. author or co-author is down to some 26.5% over the last decade and 21.8% in 2021. During the same period, the EU-27 increased their share of global research papers to 34.4% for the decade, surpassing the U.S. around 2000 (Figure 2).

As we described in our 2010 Global Research Report on the U.S., the Web of Science recorded 1,745 research papers (articles and reviews) from Mainland China in 1981, which rose to 12,100 in 1995. In this report, we find that Mainland China increased its output fifty-fold over the years from 1995 to 2021 and it has matched the EU-27 nations in research paper output during the present decade. Despite analysts predicting an inevitable plateau, the upward curve shows little sign of slowing.

Mainland China now produces more research than the U.S., despite planting an historically smaller Research Footprint on global science (Figure 3). When presented with the volume trends highlighted in Figure 2, many (not just in the U.S.) express surprise, but the up-curve is undeniable. How well does the Web of Science reflect the changing balance of publications across these countries/regions? Our focus on the U.S. and its interface with Mainland China in the internationally influential literature means that this coverage is appropriate. But Mainland China is itself becoming more diverse in output (Adams et al., 2022; Johnson et al., 2022) and when we look specifically at Mainland China, then we likely miss a growing slice of Chinese research literature that appears in Chinese-language serials (see Shu et al., 2019; and Xie and Freeman, 2019).

Note that in this report we credit 'whole papers' to each country/region that has an author or co-author. Thus, a paper with co-authors in the U.S. and Mainland China counts once in the global tally and once in the tally for each country/region, not as a 0.5 credit for each. This practice differs from some analysts who fractionally assign credit, but we choose not to infer that fractionation confers any additional precision or accuracy. Since global publication output is continually rising, we also use world shares to capture relative growth rates across countries/regions.

Figure 2.
Annual total output of research papers in all research fields for the U.S., the European Union (EU-27) and Mainland China published in journals indexed in the Web of Science, 1995-2021.



Research portfolio

The U.S. 'footprint' in research remains extensive and diverse (Figure 3) but its research subject diversity has declined because the science budget expanded much faster in biomedicine than in technology areas (Figure 4), while other countries/regions have diversified and grown to challenge its historical strengths.

In April 2010, White House Science Advisor John Holdren, addressing a meeting of the American Association for the Advancement of Science, observed, "We can't expect to be number one in everything indefinitely." His comment sparked controversy among some, who saw this as a lowering of research aspirations for U.S. government leaders. Others saw the remark as nothing more than an acknowledgement of reality – especially in light of the increasing globalization of research and the rise of many more nations competing at the frontiers of science.

Research portfolios are not evenly balanced across countries/regions, with different decisions made according to history, economy and natural resources. With regard to specific fields, over the 1980s and 1990s the U.S. increased its federal funding for biological and biomedical sciences by about 50% in preference to funding for basic and applied research. In particular, funding for the National Institutes of Health, part of the Department of Health and Human Services, increased faster than funding for research channeled through the National Science Foundation (NSF), the Department of Energy, the Department of Defense, the National Aeronautics and Space Administration (NASA) and other agencies. That investment built on a U.S. skew already noted in an international study by the U.K.'s Science Policy Research Unit (Martin and Isard, 1990).

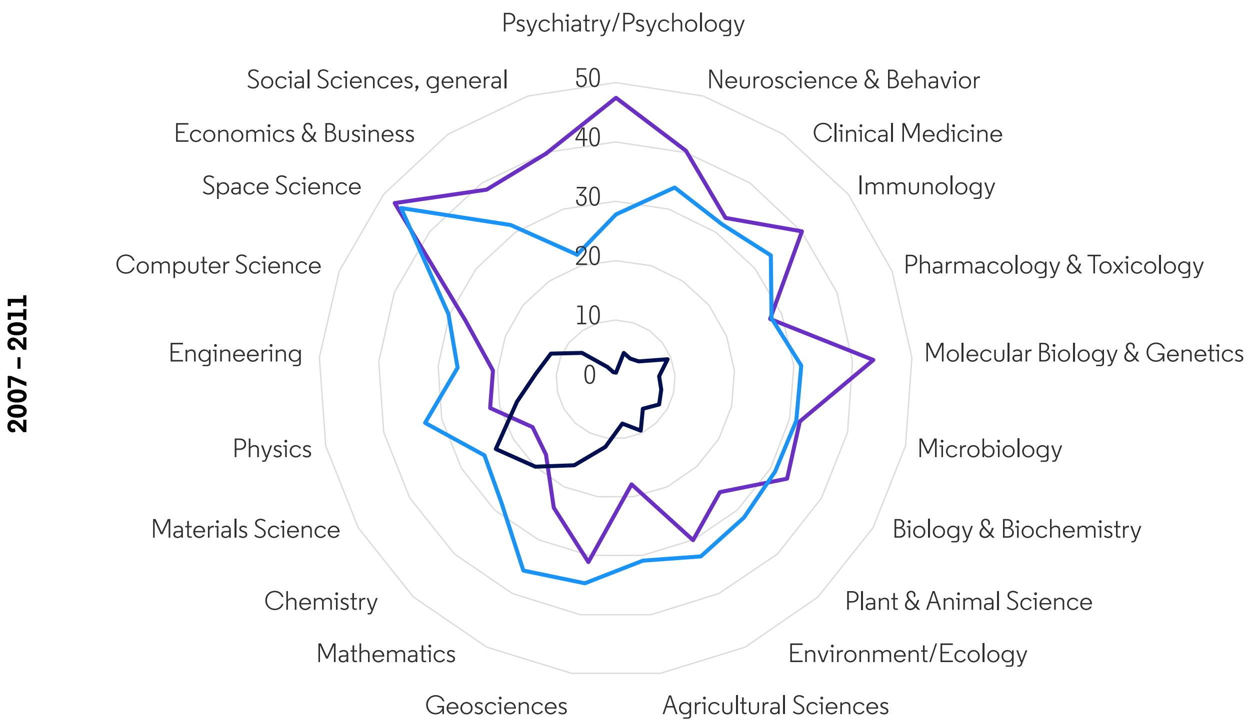
As a result, U.S. research in the physical sciences and engineering took a back seat to the biological sciences just at the time when Asian countries/regions with strong legacy industrial bases were investing substantial sums in research in engineering, physical sciences and technology. Moreover, the NSF shows that the area of physical sciences (including engineering and computer sciences) has attracted a large number of international U.S. graduate degree recipients (66.4% of 2018 engineering postgraduates were temporary visa holders). Those who choose to remain in the U.S. create significant domestic benefit, but those who leave the U.S. after graduation constitute a brain drain of highly skilled professionals who go on to contribute to innovation in any other modern, knowledge-based economies in which they are employed.

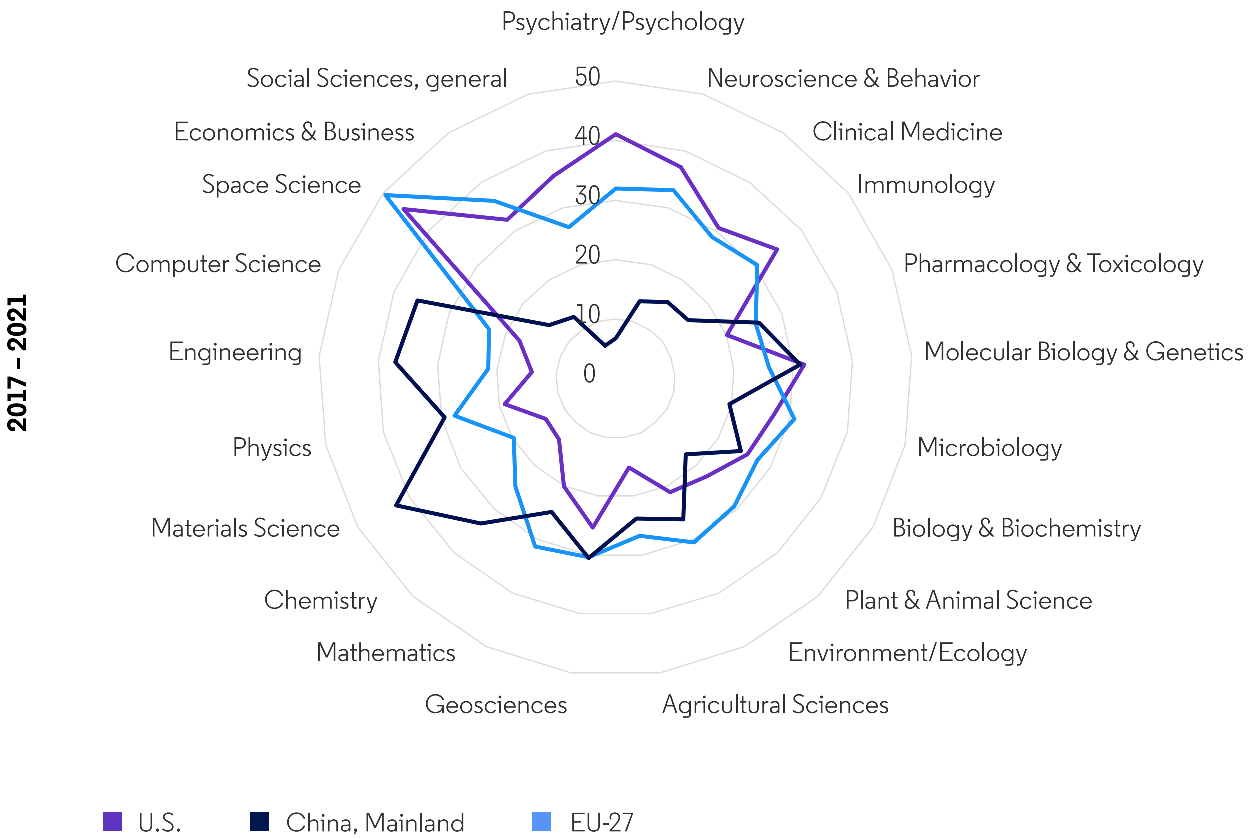
The Research Footprints in Figure 3 show that, taking the publication output data over two five-year periods, Mainland China's productivity was – as noted – still smaller than the U.S. but its presence in many areas of research has grown substantially. This graph shows world shares (not total count of papers) in each major research area represented by a journal-to-field categorization scheme developed for Essential Science Indicators (ESI)™. For example, the global output in Clinical Medicine was around 1.1 million papers in 2007-2011 of which the U.S. had 32.9%, falling to 30.7% of 1.75 million papers in 2017-2021, while Mainland China produced 4.3% rising to 15.6%. In Materials, the global total was just under 295,000 papers in 2007-2011, growing to 675,000 in 2017-2021 within which Mainland China's share rose from 23.4% to 42.6% while the U.S. share fell from 16.1% to 13.6%.

Mainland China's focus – and its greatest share of world output in major fields – is shaped by a history rooted in industrial R&D and is oriented to engineering, materials, the physical sciences and mathematics. By contrast, political and policy factors in the U.S. have tilted budget allocations to health-related research and the social sciences. Both these profiles may be compared with that of the EU-27, which collectively had a very similar spread of research to the U.S. across biomedical fields but a greater share of world output than the U.S. in fundamental biology research and a much greater share in physical sciences and engineering.

It is notable from Figure 3 that Mainland China is not only increasingly dominant in those technology areas identified by Vought and Droegemeier as essential to U.S strategic development but also that it is strongly expanding into the biomolecular areas where the U.S. has retained strategic leads hitherto.

Figure 3.
Research Footprint of national/regional share of Web of Science indexed papers (articles and reviews) published by the U.S., Mainland China and the EU-27, grouped by Essential Science Indicators subject categories. The radial axes display proportion of world output within category for the periods 2007-2011 and 2017-2021 and are arranged sequentially by biomedical sciences, through physical sciences to engineering and then social sciences.



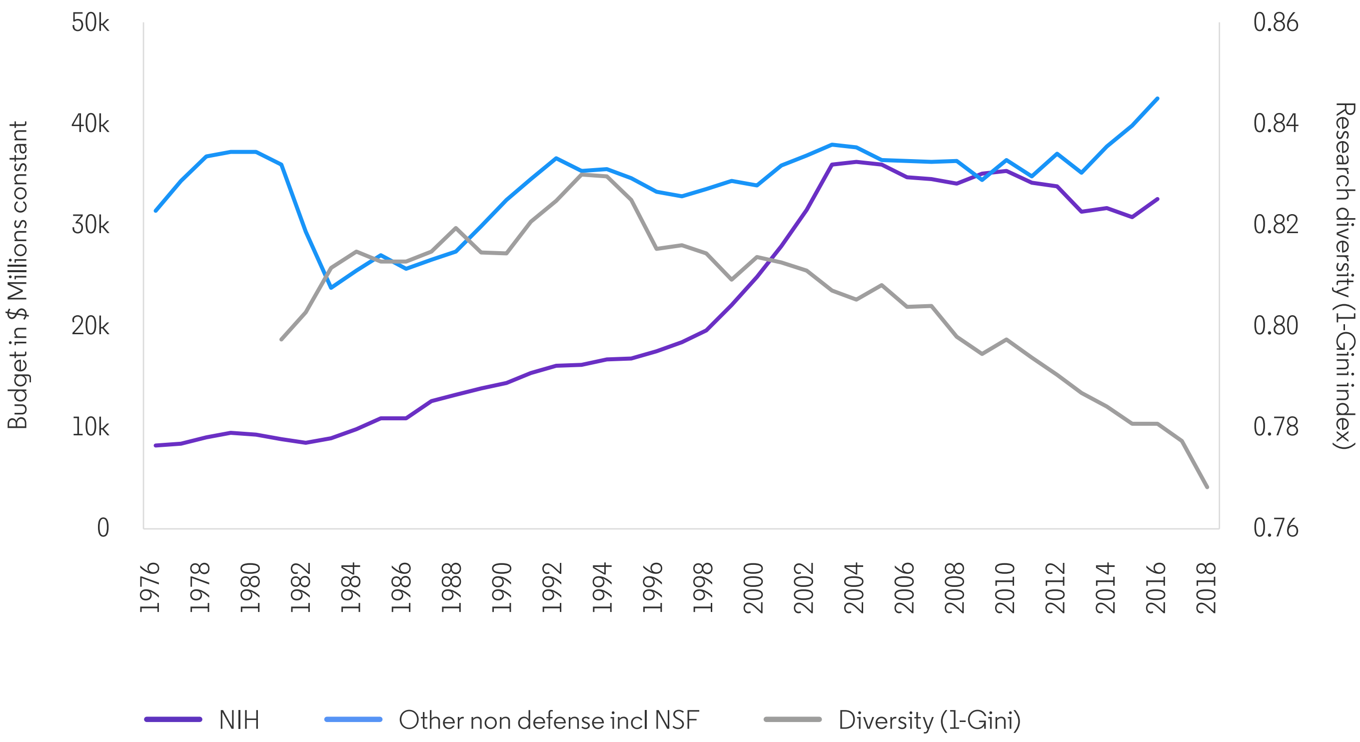


The skew in U.S. research investment developed over several decades. Budgets for the NSF and in areas such as energy and space research fluctuated after the early 1990s, while the budget assigned to the National Institutes of Health (NIH) has inexorably grown. As many have observed, no one ever lost votes by giving money for health research. Whether this achieved higher quality research and researchers is less certain (Alberts et al., 2014) but the consequence is quite clear: the NIH now receives almost half the U.S. civilian R&D budget; core engineering and technology does not. Within the U.S. research base this has resulted in an increasing degree of specialization, reflected in a rising unevenness of output across research categories compared with other G7 nations. (Figure 4)

The CHIPS Act of 2022 attempts to reverse some of these trends by authorizing an increase in the budget for the NSF by $36 billion, Department of Commerce by $11 billion, National Institute of Standards and Technology by $5 billion, and the Department of Energy by $30.5 billion over the next five years. Although the core funding from the NSF is still focused on curiosity-driven research, in April 2022 it created a new Directorate for Technology, Innovation and Partnerships to focus on use-inspired research to support translational research and partnerships between the NSF and industry.

In our 2021 ISI Global Research Report *Subject diversity in research portfolios*, the ISI began measuring the specialization of a country/region's research portfolio by indexing the spread of their publications against a world average, to take account of natural variation in field size and publication rates. National activity across categories can then be tracked by a Gini index, measuring the disparity between the actual spread of output and conformity to the global norm. U.S. research specialization started to increase (diversity across subjects started to fall) in the early 1990s when research allocations across science stalled and further increases focused on the NIH budget. U.S. research subject diversity continues to decline even today. This is contrary to the trend in almost all other major research economies, which have shown increasing evenness and diversity over the last 25 years (Figure 4; and see Adams and Szomszor, 2022).

Figure 4.
The U.S. publicly funded R&D budget and its growth between 1976 and 2016 in constant dollar values (adjusted for inflation). The 'other' line includes the NSF, NASA, DOE, EPA and other agencies not including defense expenditure. U.S. research diversity (calculated with the Gini index) increased with the rising science budget in the early 1990s and has since fallen as health research spending alone rose.



Research impact

The U.S. is strong but no longer dominates the research landscape as it did, sharing this on an increasingly equal basis with other G7 nations and at close to eye level with Mainland China. Profile analyses reveal that more U.S. papers are now of world average citation impact (an indicator of utility, influence and significance) while competitors are producing relatively more papers of the highest citation impact (Figure 5).

An important qualification to any notion of a weakening in U.S. research leadership is the consideration of research influence or impact. Bornmann et al. (2018) analyzed highly cited papers and the research those influential papers cited. They concluded that, "China still belongs to the low contributors … [in terms of] the cited references in top-1% articles … the results do not support a decreasing trend for the U.S.; in fact, the U.S. exceeds expectations (compared to its publication share) in terms of references in the top-1% articles."

Relative volume of output reflects activity and capacity in a field, but it is nothing without the quality that leads to academic, economic and social impact. This is conventionally tracked by counting the numbers of citations a research publication receives from later work. Papers with more citations are generally recognized as having a greater influence or 'impact' than papers with few or no citations. Using the citation networks in the Web of Science, we can count the number of citations to a paper and then, because citations accumulate over time at a rate that is field dependent, we must compare that count to the average for the relevant field and the year of publication to get the Category Normalized Citation Impact (CNCI).

Citation data distributions are very skewed so, rather than taking the average, we sort the CNCI values into groups relative to world average (which is 1.0) and visualize the proportion in each group as an Impact Profile which shows the spread of performance rather than burying this information in a single point metric (Adams et al., 2007). A profile is essential to proper understanding of research performance because we see that while the U.S. has an average CNCI greater than 1.0 (above world average), it nonetheless has many papers that are below average impact or even uncited, as indeed does every country/region.

Impact Profiles (Figure 5) show us shifts across time (early [2007-2011], mid [2012-2016] and late [2017-2021]) for the U.S. and country/region comparisons with Mainland China, Germany and the U.K. When examining these Impact Profiles, note where the curve peaks relative to world average and to comparator curves, how much of the activity lies above the world average, and the relative positions of each curve at the right-hand side in the categories with greatest impact.

While the U.S. had relatively more uncited papers in the later period (2017-2021), this is not significant because the most recent papers may not have had time to be recognized and cited in even newer literature. What is significant, however, is that for a very large output volume – which should stabilize other metrics – the U.S. Impact Profiles curves shifted left (towards lower impact categories) in the later five-year period. In fact, the principal change in the profile is the greater proportion of papers in the central hump, around world average, than in the early and mid periods.

How does this change compare with other countries/regions? In the early period (Figure 5b) it is evident that the U.K. and U.S. were publishing relatively more highly cited papers (>4 times world average) than Germany and these three were well ahead of Mainland China, which had a much greater proportion of papers cited less often than world average. In the mid period (Figure 5c), Germany appears to be catching up with the two leading countries/regions and Mainland China's performance is now more comparable to the others. In the late period (Figure 5d), the U.K. has moved marginally ahead of others, Mainland China has relatively fewer uncited and slightly more low-cited papers, but it is in the more highly cited categories that the U.S. performance is essentially indistinguishable from that of either Germany or Mainland China. The most research-active countries/regions tend to be cited soonest after publication (Adams, 2018) at a point when papers from other countries/regions will be largely uncited.

On a per paper basis, the average influence of U.S. papers, as indexed by CNCI, maintained the U.S.'s substantial lead over other countries/regions through the last half century. Over the last two decades, EU nations began to close that impact gap and it is evidently no longer possible to say that Mainland China's productivity has yet to deliver excellent research outcomes. Mainland China is reducing the proportion of its papers that fall below world average and producing many more papers that rise into the categories above world average. Mainland China is now clearly competitive with other leading countries/regions at the most highly cited end (> 8 times world average).

Figure 5a – 5d.
Impact Profiles for the papers (articles and reviews) published by the U.S., Mainland China, the U.K. and Germany during three consecutive five-year periods: early (2007-2011), mid (2012-2016) and late (2017-2021). Data are displayed as a proportion of output for each curve across impact category groups relative to world average. Uncited papers are shown as histograms to the left, followed by cited papers shown as a smoothed curve across four impact categories below and four above world average (= 1.0). The most influential papers, the CNCI of which are >4 times world average, are to the right of the curve (see Adams et al., 2007). Note: Figure (5a) shows the U.S. profile for all three periods while the other three (5b – 5d) compare the four countries/regions together.

Figure 5a.

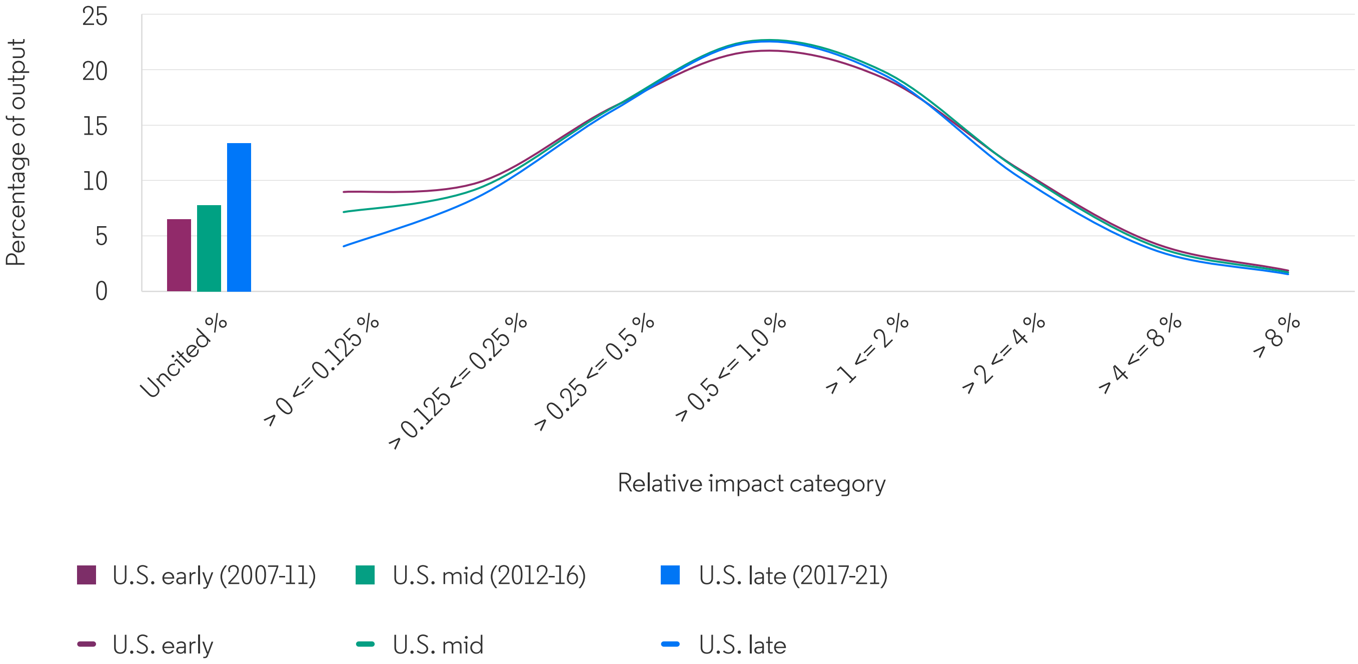


Figure 5b: Early (2007-2011).

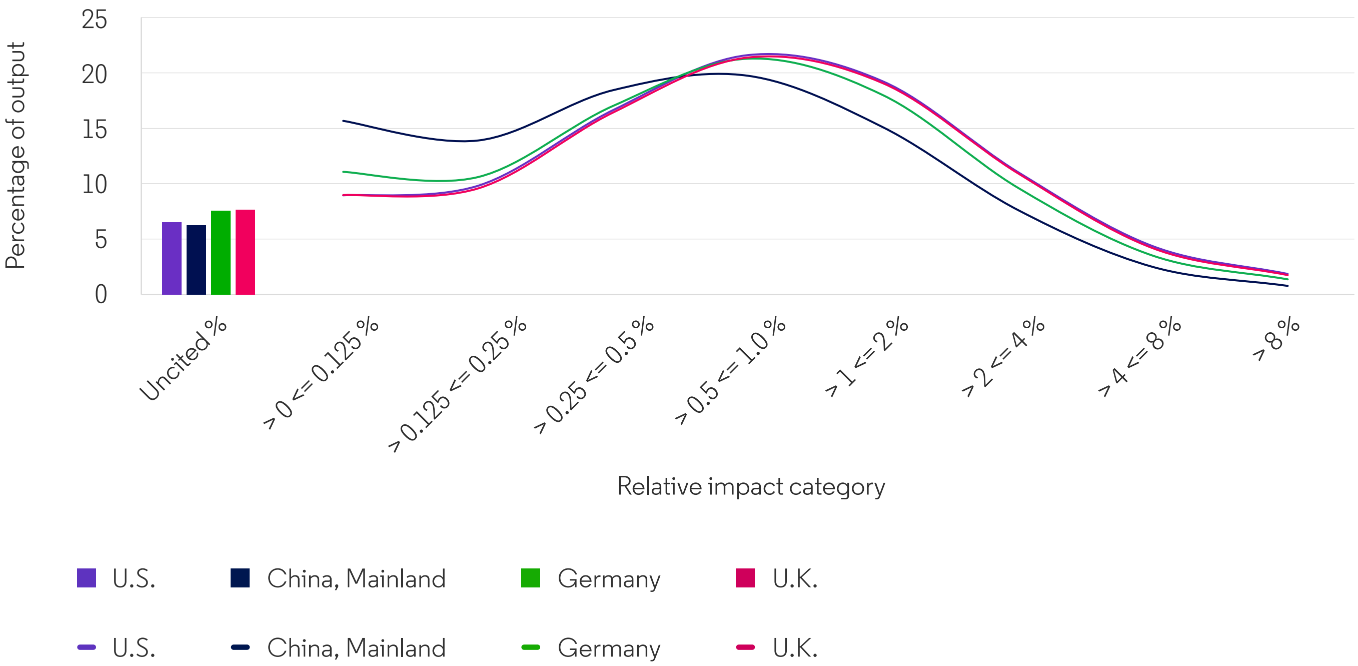


Figure 5c: Mid (2012-2016)

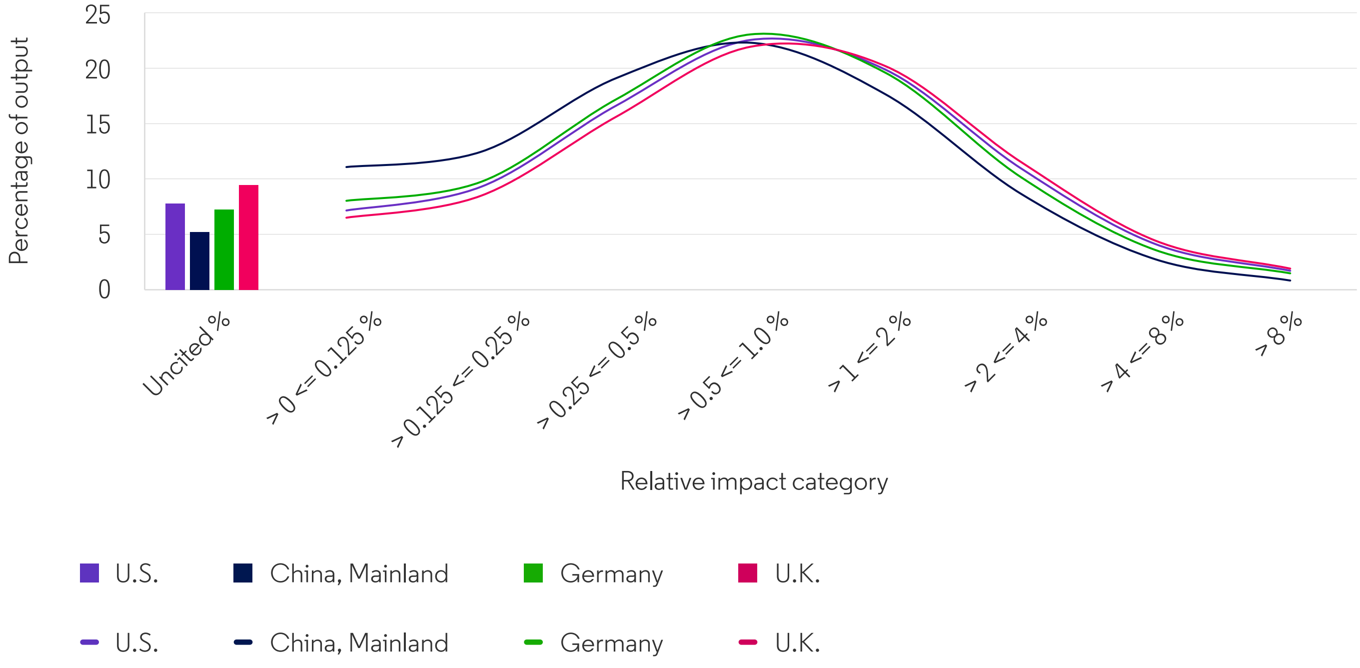
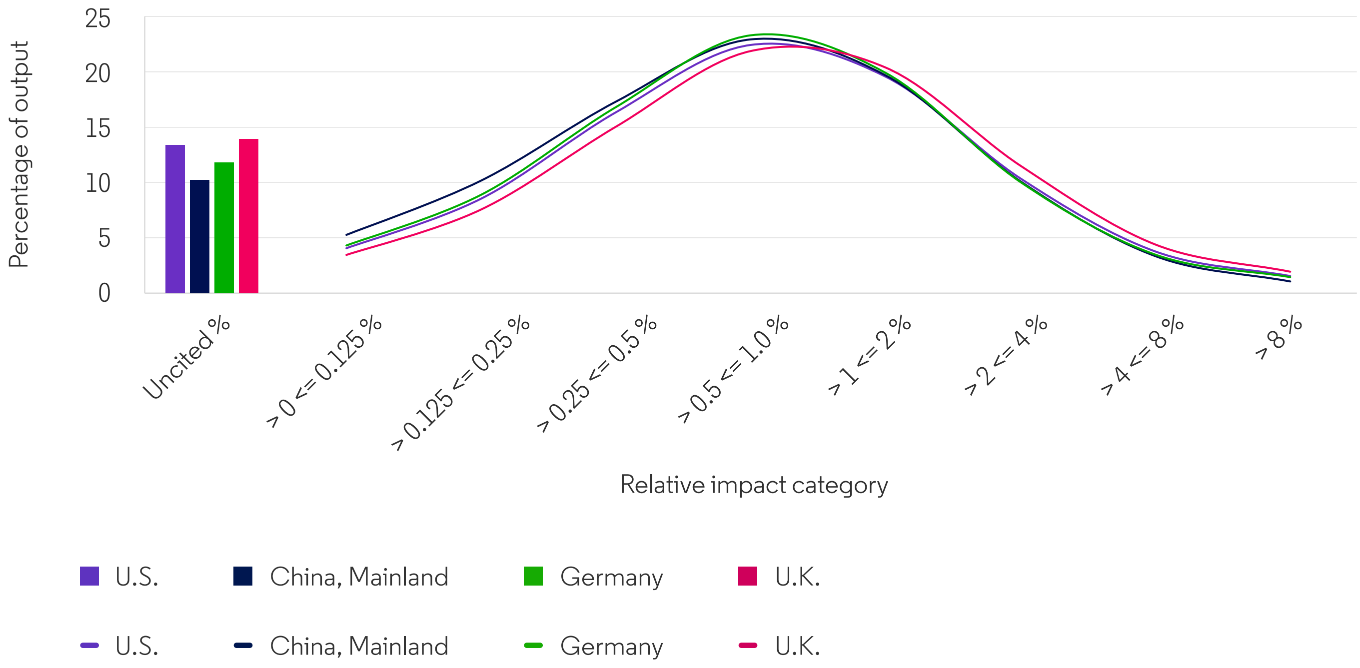


Figure 5d: Late (2017-2021)



Research collaboration

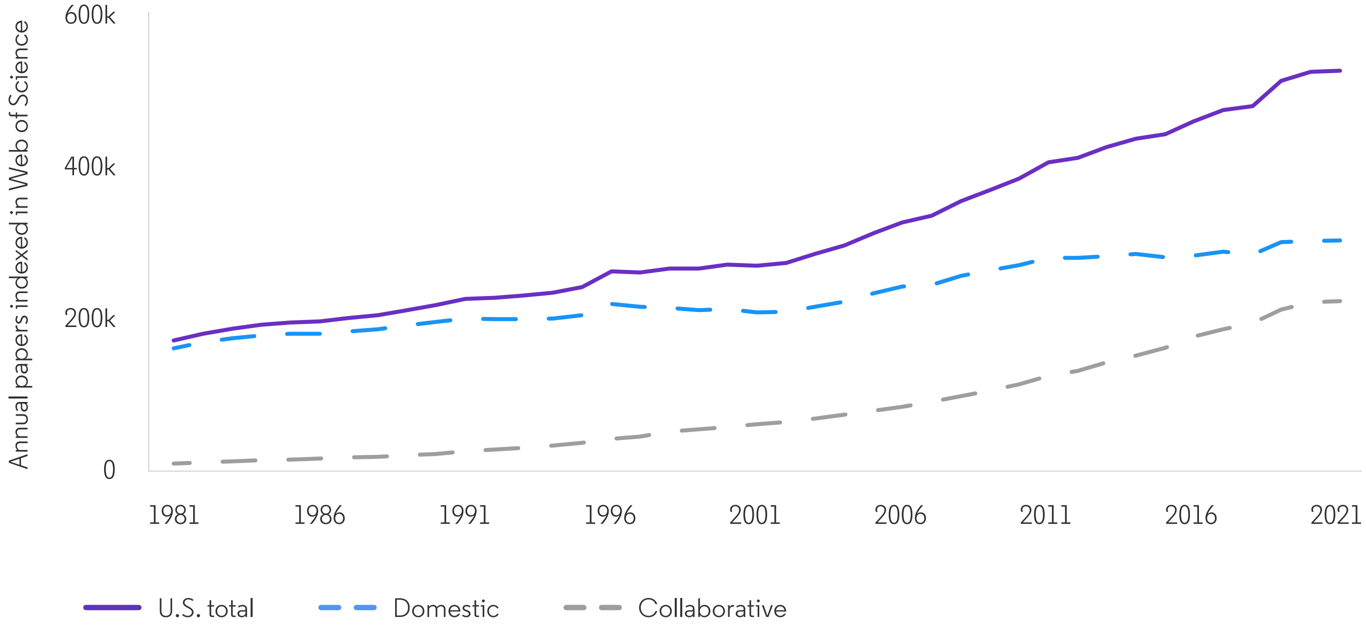
International research collaboration has expanded pervasively across the globe. Most growth in U.S. research output is attributable to collaboration (Figure 6), which has doubled for major traditional partners such as the U.K. and Germany and quadrupled with Mainland China (Table 1). The citation impact of collaborative papers is greater than domestic research and has mitigated a decline in overall U.S. impact indicators (Figure 7).

A factor that affects all recent research indicators is the increasing density of international collaboration, with many research publications having authorship from several countries/regions. This is a phenomenon that has increased globally since the 1980s, when such collaboration was rare, and is driven by lower-cost travel and the Internet. In the 1990s there was a surge in bilateral collaboration which was in turn overtaken after 2005 by multilateral collaboration.

As the world became increasingly collaborative, excellence talked to excellence. The cutting edge of research shifted from leading academic institutions in the early 20th century, to investment by nation states after 1945, and is now led by an international network of outstanding institutions (Adams, 2013). More than half of the research output of many countries/regions is now co-authored with researchers from another and the internationally collaborative part of the research base sees the greatest rate of citations from other researchers (Narin et al., 1991). In this slice of research, it is the top institutions that are collaborating trans-nationally with one another.

There has been a shift in the balance between that U.S. research output that belongs wholly to the country and that shared with one or more collaborators. This might seem potentially deleterious to U.S. research strengths but, on the other hand, there is widespread evidence that collaboration delivers work of greater impact leading through to more significant technological, economic and societal gains. In fact, the growth of U.S. output over the last 40 years (Figure 2) has been driven primarily by the increase in international collaboration, whereas domestic research has not kept pace (Figure 6).

Figure 6.
The growth of U.S. research output and the components attributable to the domestic research base alone and to collaborative international publications.



The U.S. has been one of the most sought-after partners in the global network. It is the most frequent partner for many other countries/regions, and it benefits itself and its partners through collaboration. Yet, paradoxically, it is also one of the least internationally collaborative (Adams and Pendlebury, 2010), explained partly by its opportunities in domestic collaboration and partly by the sheer scale of the U.S. enterprise (and note that Mainland China is also relatively low on collaboration).

During the decade after 2000, Mainland China grew to be a preferred U.S. partner (Wagner et al, 2015). Our data show that while total U.S. output expanded by a factor of 1.37 between 2007-2011 and 2014-2018, U.S. research papers with a Mainland China co-author increased by a factor of 4.38 (see Table 1).

Most other countries/regions approximately doubled their U.S. collaboration volume in this period, expanding slightly faster than U.S. domestic volume as international engagement generally increased but at nothing like the same rate as Mainland China.

The U.S.'s most frequent partners were once trans-Atlantic. Table 1 shows that those partners have been displaced by the rise of research links with Mainland China. If we sum the EU-27, we find that about 15% of recent U.S. output was co-authored with one or more of those countries/regions while over 10% had one or more Mainland Chinese author addresses. The U.K., the largest European partner and an established collaborator, contributed to 6% of U.S. output, just over half of Mainland China's share.

How important to the U.S. research base are the major partners in Europe and Mainland China? In 1995, Mainland China researchers co-authored less than 0.5% of U.S. output; by 2000 that had risen to 1%; in 2010 it was 4.3%; and as noted, recent data show that one or more researchers based at a Mainland Chinese institution will now be co-authors on over 10% of U.S. research. However, that share seems to be levelling off as Mainland China increases the range of its partners in Europe and Asia. It is also notable, for policy observers, that average share is far from evenly distributed across research fields, as we will show below. Support for these collaborations flows both ways. Yuan et al. (2018) found that U.S. researchers are the most frequent of 75 international partners on grants from the National Natural Science Foundation of China (NSFC), appearing on more than half the grants that had an overseas collaborator.

Table 1.
Volume of internationally coauthored publications for most frequent U.S. partner countries/regions. These counts of papers (articles and reviews) published in journals indexed in the Web of Science have at least one U.S. co-author and at least one author with an address in the country/region indicated. The ratio between the early and late periods is an indicator of the growth in these partnerships.

	2007 – 2011	Growth ratio	2017 – 2021
U.S. total	1,839,628	1.37	2,517,935
China, Mainland	59,666	4.38	261,503
U.K.	72,286	2.10	151,443
Germany	64,453	1.84	118,806
Canada	63,681	1.81	115,175
France	28,863	2.58	74,554
Italy	41,995	1.83	77,034
Japan	36,221	1.96	70,831
Netherlands	36,593	1.53	56,017
South Korea	24,582	2.19	53,750
India	27,369	1.83	49,984
Russia	13,885	2.86	39,695

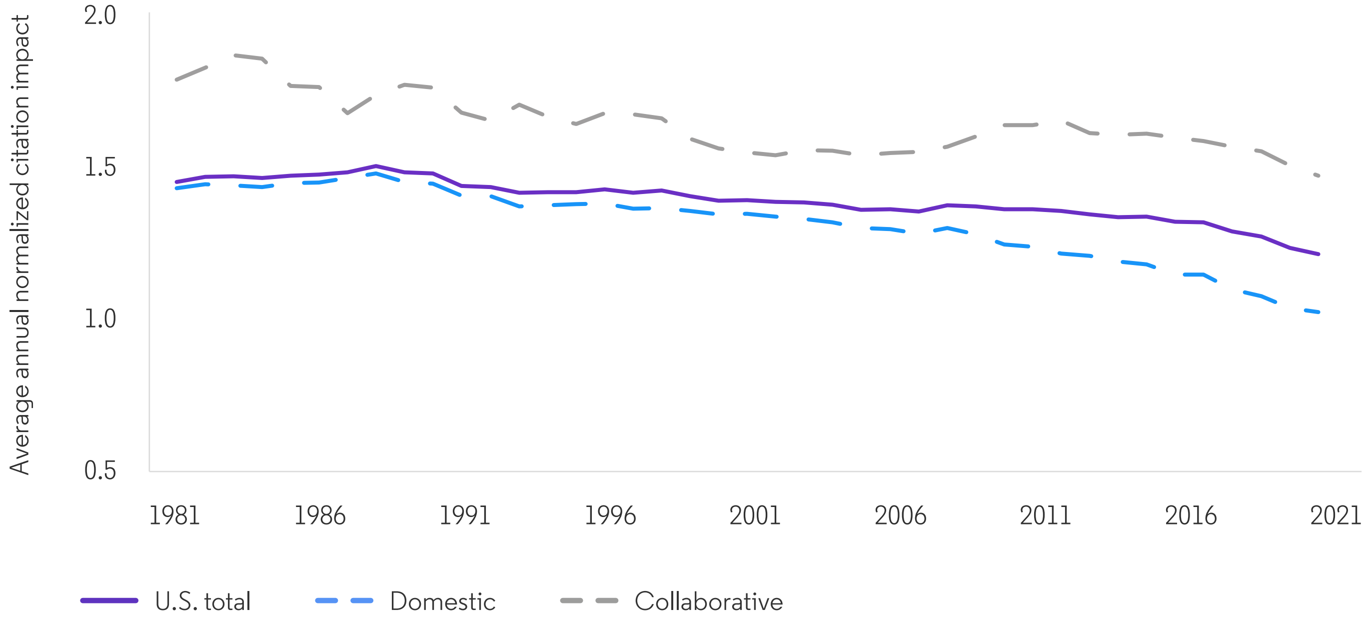
Figure 6 indicated that the absolute growth of U.S. domestic-only research output has levelled off, as it has done in other countries/regions (Adams, 2013), which means that U.S. total annual articles and reviews could have declined without expanding collaboration, particularly with Mainland China. This surprising nuance, noted also by Lee and Haupt (2019), is intriguing and shows how rapidly Mainland China has come to play a significant role in the U.S. research base, while at the same time the U.S. global position appears to have been under some pressure. It requires policy attention but, again, need not by itself suggest anything more than maturity.

How can we assess the benefit to the U.S. that international collaboration brings? Tangible benefits clearly emerge from shared use of facilities, including powerful instruments beyond the budget of any one country/region. There is also access to additional capacity and intellectual competency, and this may enable entry to research fields not currently supported. Less tangibly, it should mean engagement with an international discourse on discoveries and opportunities, which accelerates research progress. Not being at 'the bench' means not hearing the chat.

The post-1945 scale of R&D investment by the U.S. made it by far the most research-dominant country/region in the 1980s when measured by average CNCI. Since then, the global research base has expanded and diversified, and many other countries/regions now contribute to the global reference pool. Since the U.S. was the historical leader, it is inevitable that its average citation impact compared to the global benchmark would fall as others improved.

So much is a given. What is less apparent is the relative contribution made to any overall headline figure by the domestic and internationally collaborative components. In fact, the U.S. headline 'average national citation impact' is increasingly dependent on the international component while the CNCI of purely domestic research publications has declined close to world average and is on a falling trajectory. (Figure 7)

Figure 7.
Category Normalized Citation Impact (an indicator of research performance) for U.S.-authored articles and reviews published in journals indexed in the Web of Science. Data are shown for the overall U.S. average and for two sub-sets of papers: those that had only domestic authors; and those that were collaborative with an international co-author.



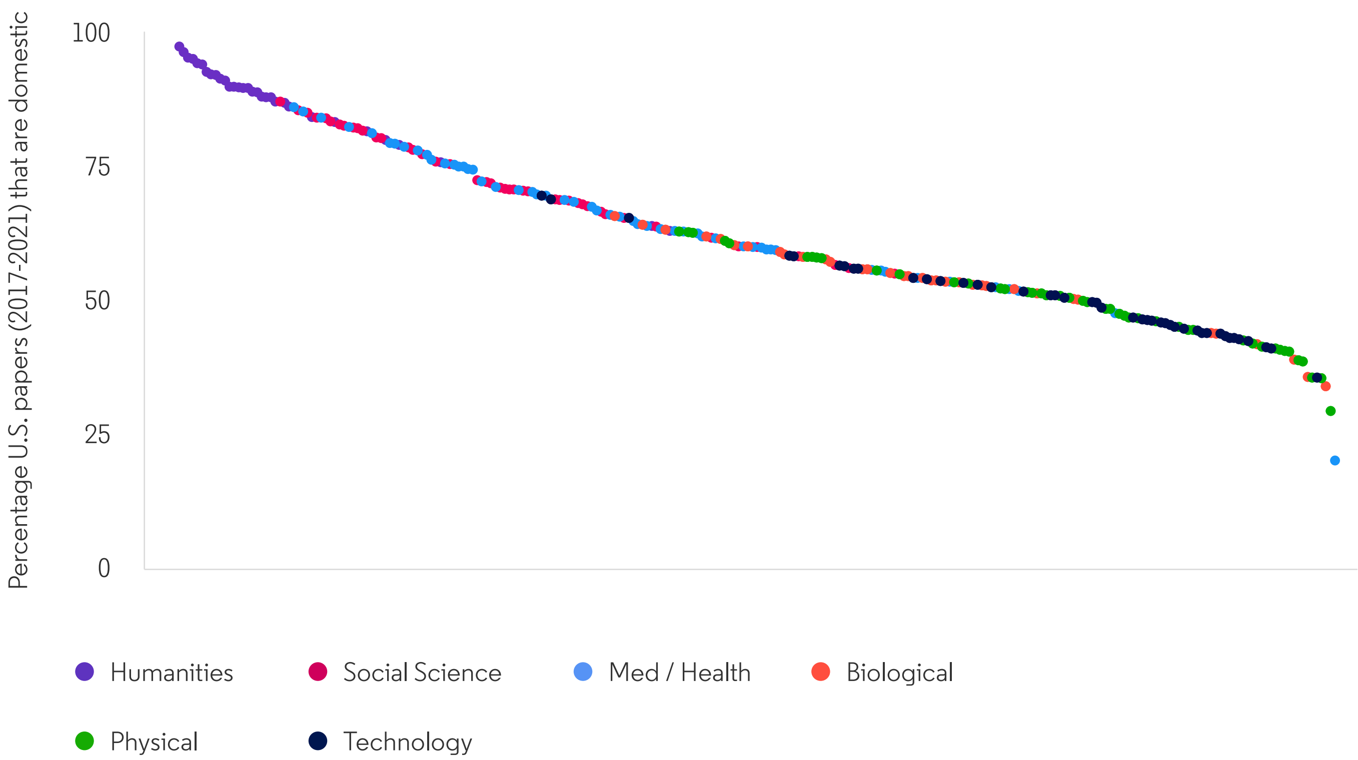
Comparative research balance

U.S. research collaboration is greatest in the physical sciences and in technology subjects (Figure 8). It accounts for over 50% of output in most science/engineering areas and includes a diverse network of partners. Mainland China is the most frequent partner in technology research and is as frequent as the U.K. and Germany in physical sciences (Figure 9).

A country/region's research portfolio is rarely aligned with the overall global balance of subjects. Most have strengths and weaknesses and specialize in particular areas, although historical investment often aligned to socioeconomic need and policy priorities such as food, health and key industrial sectors. Figure 3 illustrates the different research footprints of the U.S., the EU and Mainland China. Collaboration is also more concentrated in some areas than others and this affects the extent to which research in those areas is supported primarily by domestic capacity or through partnerships, with partnerships inevitably implying shared intellectual property.

When data are analyzed by Web of Science journal subject categories, grouped into cognate research areas at 'Faculty' level, domestic percentages are least in the physical sciences and technology, intermediate in biomedical areas and high in humanities and social sciences. Although the subject categories vary considerably in size, related to the numbers of journals in each area, there is no correlation between volume and the percentage of papers that are purely domestic (Figure 8).

Figure 8.
Subject categories ranked by descending order of percentage of papers published in journals indexed in the Web of Science (2017-2021) that have purely U.S. domestic authorship. Subject categories are coded by broad 'Faculty' level groups.

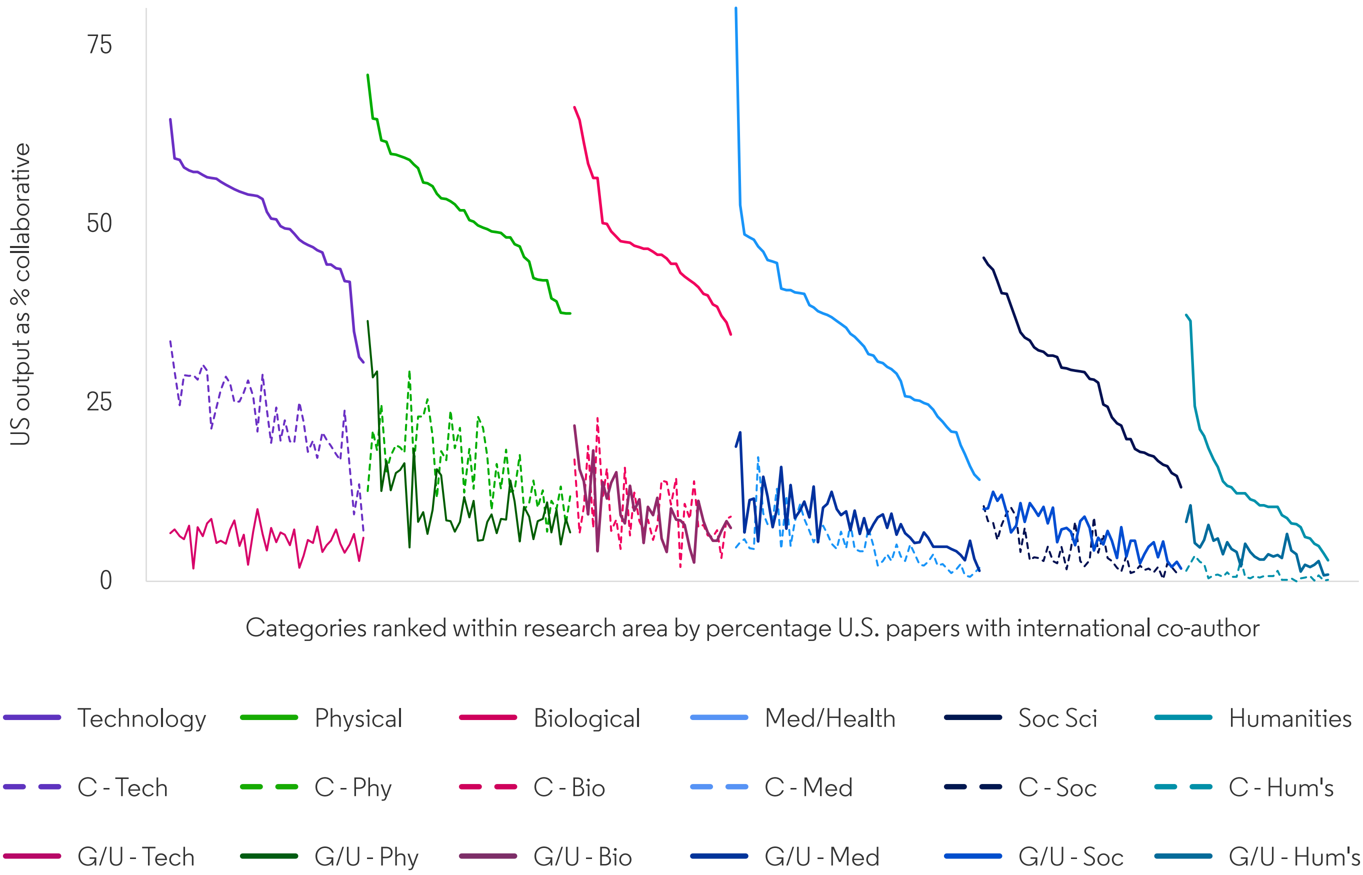


The physical sciences and technology areas are the subjects where the U.S. has the greatest degree of international collaboration and the smallest component of purely domestic research output, often less than half the total publication output. It therefore both gains most from partners in these areas and shares the most intellectual contribution with those same partners.

International collaboration is not evenly spread among countries/regions in these subjects. The three most frequent partners for the U.S. are Mainland China (in Asia), and the U.K. and Germany (in Europe) (Table 1). Mainland China is a much more frequent collaborative partner in technology subjects and in most of the physical sciences, notably contributing to 25% or more of U.S. papers in Telecommunications, Artificial Intelligence and Information Systems, Remote Sensing, Metallurgical Engineering, Environmental Engineering and Imaging Science. Mainland China-based researchers also co-author 20% of recent semiconductor research papers with a U.S. author. However, note that an equal fraction is shared collaboratively with other countries/regions so the U.S. partnership network is diverse. It benefits from shared costs, effort and intellectual property with many countries/regions, not just its most frequent partners.

The U.K. and Germany are generally the more frequent collaborators in medical and health sciences. Note that the exceptionally high level of international collaboration for one of the medical fields refers to Tropical Medicine and this encompasses nearly 80% of U.S. publications in this area. Europe partners with the U.S. on more than 25% of papers in Astronomy and in Nuclear and Particle Physics, but these are areas of intense and widespread collaboration associated with major international facilities and massively multi-authored papers. In broad-based biological sciences the level of collaboration between the U.K./Germany and Mainland China is similar, which is a reflection of Mainland China's investment and growth in these areas.

Figure 9.
The percentage of U.S. papers published in journals indexed in the Web of Science (2017-2021) that have international co-authorship, broken down into those that have a co-author located in Mainland China (C) and those that have an international co-author located in Germany or the U.K. (G/U). Subject categories within each broad research area are ranked by the percentage of U.S. papers that have an international co-author.



U.S. geographical diversity

In common with other post-industrial economies, the U.S. has sought to address over-concentration of its innovation and development resources by structured funding directed to areas of relatively weak research capacity (Table 2). The evidence indicates there has been a shift to greater equity in the distribution of excellence through rising impact in U.S. states of historically low research output (Figure 10).

It is widely recognized that U.S. research activity is far from evenly spread across the country. Since the principal justification for public investment in R&D is that it makes a significant contribution to technological advancement, economic well-being and the quality of life, any disparity between states might be deemed a matter of concern. Similar challenges are being faced in other countries/regions because of changes in the nature and distribution of industrial activity, the shifts in economic focus and the mobility of people. In the U.K., for example, recent governments have spoken of a leveling-up agenda, though this has not yet translated into any tangible change in research distribution. In Germany, enormous sums have been invested in rebalancing the economy of the West and East.

In 2017-2021, U.S. researchers published around 2.5 million papers in journals indexed in the Web of Science. Around 465,000 of those had an author in California while fewer than 10,000 were published in five states. There is an evident concentration of activity on the West and East coasts and a comparative paucity of research activity in the geographic middle of the nation.

Table 2.
U.S. states publishing the most and fewest papers in journals indexed in the Web of Science (2017-2021).

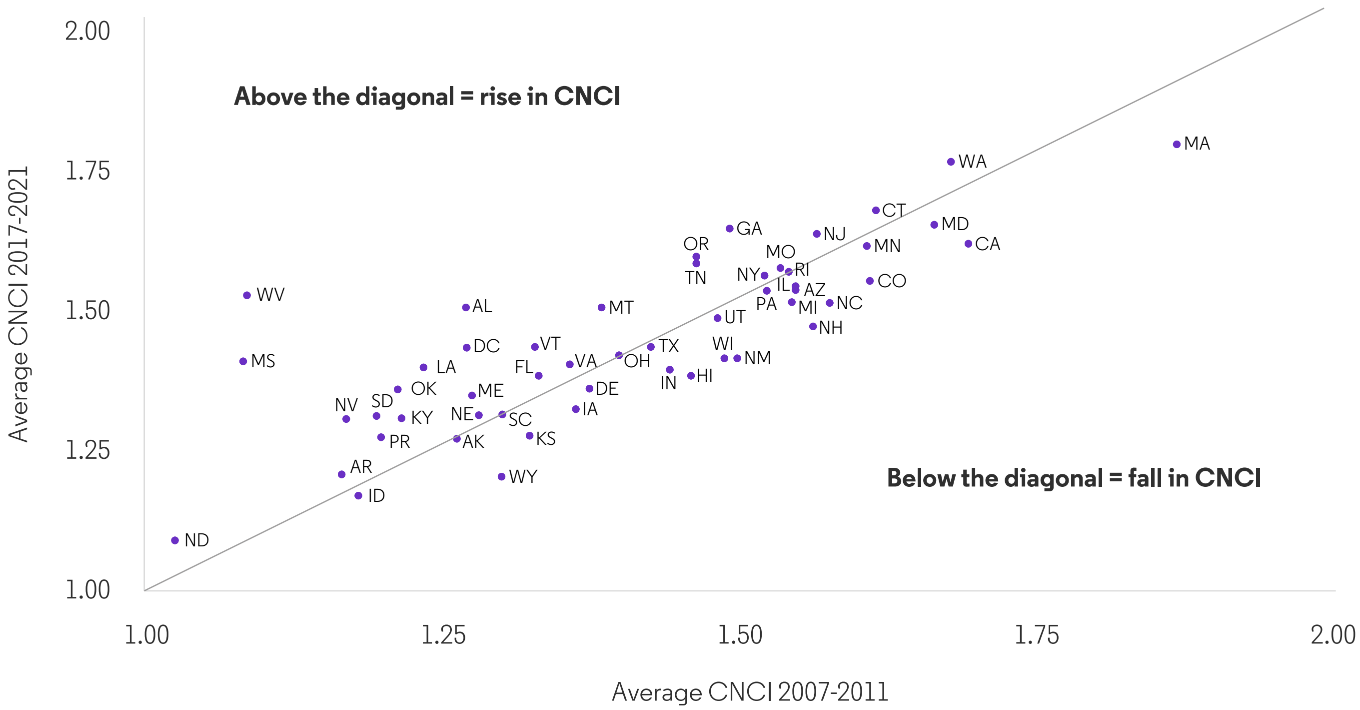
Most prolific		**Least prolific**	
California	463,120	Arkansas	17,165
New York	310,768	Delaware	14,767
Massachusetts	284,219	Nevada	14,210
Texas	238,618	West Virginia	13,316
Pennsylvania	204,120	Idaho	12,032
Maryland	192,598	Montana	10,493
Illinois	161,567	Maine	10,162
Florida	142,576	Vermont	9,848
North Carolina	139,564	North Dakota	7,919
Ohio	137,730	Alaska	7,072
Michigan	126,125	South Dakota	6,604
Georgia	105,772	Wyoming	6,026

In 1979, NSF created the Experimental (which changed to Established in 2017) Program to Stimulate Competitive Research (EPSCoR) program to enhance the research competitiveness of targeted jurisdictions (state, territory or commonwealth). Similar programs now exist in the NIH, NASA, and the Departments of Agriculture, Defense and Energy. NSF's EPSCoR program funding is limited to jurisdictions that receive 0.75% or less of total NSF research and related activities funds over the most recent three-year period. Currently 25 states and three territories are eligible for EPSCoR funding, which include all the states in the 'Least prolific' column in Table 2. Of these states, Alaska received the highest percentage of funding from NSF over FY 2018-FY 2022 at 0.7%.

There are two principal indicators of research activity and performance: quantity, by numbers of publications as in Table 2; and quality, by normalized citation counts. Increase in output will take time to show as capacity is gradually built, and it is essential that this should not be mere volume but founded on and fed by quality ideas, projects and outcomes. Figure 10 shows the changes that can be detected at this stage in the relative quality of past and current research publications.

It is interesting to note that some states that have been prolific in their historical publishing patterns have seen some drop in their recent relative CNCI whereas there is a spread of states with smaller output that have evidently improved the average citation peformance of their papers. The least well-cited quartile of states, with an average CNCI of 1.19 in 2007-2011, saw their citedness rise to 1.33 in 2017-2021 whereas the most cited saw a drop from 1.64 to 1.60 over the same period. It is worth bearing in mind that measuring change has its challenges. Some of the changes could be statistical variation and others may be due to universities consolidating research efforts and creating pockets of excellence. Recently, funding agencies have been requiring greater geographical and demographic diversity among the research teams they fund, resulting in reseachers in EPSCoR states being involved in collaborations with researchers with a good record of receiving funding from federal agencies. Further analysis into the relationship between targeted funding such as the EPSCoR program should disagregate the contribution of domestic-only and internationally collaborative research.

Figure 10.
10-year change in Category Normalized Citation Impact (CNCI, world average = 1.0) for U.S. states. CNCI reflects the attention given to these publications by later researchers.



Conclusions

The U.S. remains a leading science and technology power, but it no longer stands alone. Building capability and innovation in engineering, in technology and in other areas critical for its research investment policy will need to start from an evidence-based reckoning of the nation's shrinking domestic capacity. International engagement offers substantial returns but that too must be done with full awareness and informed planning.

Steel and manufacturing were once the core of U.S. industry, and manufacturing capacity and expertise must be built again if the Biden Administration's aspirations for the CHIPS and Science Act are to be realized. This report confirms, however, that the decline in domestic research capacity in engineering continues. It has recently been reported that 9 of 10 working engineers will soon be active outside the U.S. And, within the U.S., more than 50% of the recipients of doctoral degrees in engineering are internationally born. The U.S. world share in engineering papers has been cut from 38% in 1981 to 15% in 2019. The EU-27 surpassed the U.S. in output in 1997, and in 2019 held a 25% share of the field.

Part of the decline may be that of any major post-industrial economy, but the research shift appears to have happened without clear awareness in policy debates. Consequent over-concentration of technological capacity was noted, and partly remedied by EPSCoR, but the overall change in balance between technology and biomedical science, driven by funding growth for NIH, was not as clearly recognized. That led to a shift in focus across the research landscape, the implications of which were not always appreciated or built into planning.

As the U.S. focus on its industrial technology capacity dwindled, so another key change was the rise of research capacity in Mainland China, which matched U.S. publication output by 2012 (as predicted in our 2010 report) and overtook the EU-27 in 2015 on an upwards trajectory. In 1981, Mainland China claimed only a modest 0.5% of world engineering papers but by 2019 that figure was close to 40%. U.S.-Mainland China collaboration accounts for about 25% of current U.S. engineering output and more than 80% of those papers are bilateral. The U.S. does and will continue to benefit from working with an acknowledged and resourceful competitor. It must do so with pragmatism and realism, not with either paranoia or wishful thinking.

The U.S. world share in engineering papers has been cut from 38% in 1981 to 15% in 2019. The EU-27 surpassed the U.S. in output in 1997, and in 2019 held a 25% share of the field.

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