Trends in the Relationship between U.S. Academic Scientific Publication Output and Funding and Personnel Inputs: 1988–2011

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Abstract

The two decades spanning 1988–2011 evidenced considerable growth in funding for academic research and development in science and engineering (S&E), and smaller growth in the number of academic researchers and in the number of academic scientific publications. After adjustment for inflation,[2] expenditures for academic R&D in S&E almost tripled during this period, rising from $17.3 billion to $49.7 billion. Throughout most of this period, funding for academic R&D in S&E grew steadily, with rapid increases from the late 1990s until around 2005 and slower growth since then. There was also steady but slower growth in the number of U.S.-trained academic researchers and in the number of annual academic sector publications.

Introduction

This working paper explores trends from 1988 to 2011 to see how the number of academic scientific publications (output) is related to funding for academic R&D in S&E and the number of U.S.-trained, doctorate-level academic researchers in science, engineering, or health (inputs). Trends are reported at aggregate and field levels. By using the 1994 Carnegie classification of institutions of higher education,[3] the paper also examines trends for different types of universities and colleges: public versus private and universities with the highest level of research activity (Research I universities) versus less research-extensive universities and colleges.

The analysis used three sources of data:

- The National Science Foundation's (NSF's) annual Survey of Research and Development Expenditures at Universities and Colleges for estimates of U.S. academic R&D expenditures from FY 1986 to FY 2009. (The survey was renamed the Higher Education Research and Development [HERD] Survey in FY 2010).
- NSF's Survey of Doctorate Recipients (SDR) for estimates of the number of U.S.-trained doctorate-level academic researchers for whom research was a primary or secondary work responsibility from 1993 to 2010.[4]
- Thomson Scientific's annual Science Citation Index and Social Sciences Citation Index for data on the number of highly cited U.S. academic publications from 1988 to 2011.

Results in Brief

The ratio of total academic R&D expenditures to publications increased from the late 1980s through 2006 and remained more constant after that time. In contrast, the ratio of total publications to researchers remained relatively stable during 1994–2011. With some variation, these trends prevailed across all types of academic institutions. These trends do not necessarily indicate diminishing returns for research expenditures, as this paper will discuss.

Trends varied by field in the ratio of R&D spending to publications. Life sciences—which has long accounted for the majority of academic R&D expenditures, a sizeable share (about one-third) of the academic doctoral workforce, and more than one-half of publications—shows a trend close to the overall pattern, with an upward trajectory in the spending-to-publications ratio in most years. After adjustment for inflation, life sciences showed the greatest increase in this ratio from 1994 to 2011 (81%). In contrast, the spending-to-publications ratio for physical sciences was nearly flat (11%). Social sciences and engineering both saw a moderate increase in the spending-to-publications ratio (roughly 20% in each field).

Overall, the ratio of articles to researchers was largely flat during the period of analysis, although there was some variation by field. There were slight increases in the publications-to-researcher ratio in social sciences, engineering, and physical sciences, particularly at public institutions. The publications-to-researcher ratio in the life sciences dropped slightly during this time, especially at private institutions.

The trends reported here do not necessarily indicate changes in researcher productivity. Many other interpretations of these trends are possible. Further research is needed to explore the broad array of factors that have affected academic S&E research and publication practices and to analyze their impact on the relationships reported in this paper.

Objectives, Methodology, Data Description, and Data Limitations

The main objective of this analysis is to illustrate trends over the past two decades in the aggregate number of academic scientific publications in relation to funding for academic R&D in S&E and the number of U.S.-trained, doctorate-level academic researchers in science, engineering, or health. Additional objectives are to determine whether the aggregate findings are replicated at various types of universities and colleges and across fields of science and engineering. It is hoped that this analysis will spur further research.

After presenting aggregate trends, this paper compares trends for the following types of universities and colleges: (1) publicly versus privately controlled institutions and (2) Research I institutions versus less research-extensive universities and colleges. Researchers from publicly controlled universities authored about two-thirds of total academic sector articles.[5] Similarly, researchers from Research I institutions authored about two-thirds of total academic sector articles.

This paper also covers the fields in which academically employed doctorate holders earned their first research doctorate in science, engineering, or health.[6]

- Life sciences: biological, health and medical sciences, agricultural sciences, and other life sciences.

- Physical sciences: astronomy, chemistry, physics, geosciences, atmospheric and earth sciences, oceanography, and other physical and environmental sciences.

- Social sciences: economics, political science, sociology, and other social sciences.

- Engineering: aeronautical and astronautical engineering; bioengineering and biomedical engineering; chemical, civil, and electrical, and mechanical engineering; metallurgical and metals engineering; and other engineering.

To account for the passage of time between funding, conducting, and publishing results of the research, this analysis compares R&D expenditures in a given year with counts of academic research personnel from the following year and with publication counts from two years after the year of R&D expenditures.[7] For example, publication counts in 2011 are compared with inflation-adjusted academic R&D expenditures in 2009 and estimates of doctoral researchers in 2010. Whenever a year is noted in the text, figures, or tables, it refers to the publication year. Further analysis could explore the use of different lag times, no lag times, or field-specific lag times.

Funding is measured as the annual S&E R&D expenditures of universities and colleges.[8] NSF surveys these institutions annually via its Higher Education Research and Development Survey (HERD) (called the Survey of R&D Expenditures at Universities and Colleges before 2010). For the years covered in this analysis, the survey was a census of academic institutions that granted a bachelor's degree or higher in S&E fields and reported at least $150,000 in separately budgeted S&E R&D expenditures in the previous fiscal year. The survey defined R&D as projects that are separately budgeted and fall under the Office of Management and Budget's (OMB's) A-21 definition of organized research. It further specified that R&D includes (1) R&D sponsored by federal and non-federal agencies and organizations and (2) R&D that is separately budgeted under an internal application of institutional funds.[9] About two-thirds of academic R&D is basic research. Applied research and development together constitute the remaining one-third.

In this analysis, academic R&D expenditures—whether for basic research, applied research, or development—are treated as if their sole purpose was to fund research that leads to publications. However, spending on academic R&D results in many other outcomes. It supports training for the next generation of science, engineering, and mathematics professionals in research practices and other advanced skills. It also funds the development of new processes or technologies that may result in patents, the curation of databases, and the purchase and maintenance of research equipment. Academic R&D funds are also spent on a wide range of administrative and regulatory activities associated with conducting research. It is beyond the scope of this paper to analyze the effects of changing priorities for the use of academic R&D funds. For example, the paper does not attempt to measure whether a growing emphasis on patenting or interdisciplinary research could affect academic R&D publication output.

Salaries, wages, and benefits are the largest component of academic R&D expenditures, constituting about 40% of these funds.[10] Other components include non-salary-related direct R&D costs (roughly 20% of total academic R&D expenditures), indirect costs[11] (around 25%), funds passed through to subrecipients (about 8%), and equipment and software costs (around 5%). Although research projects may span multiple years, the Survey of R&D Expenditures at Universities and Colleges defines current fund expenditures as operating funds actually spent by a school during its fiscal year (typically from 1 July of the preceding calendar year through 30 June of the current calendar year).

Academic R&D personnel are persons who received their first doctorate degrees in science, engineering, or health[12] from a U.S. institution; work in 4-year universities, medical schools, or university research institutes; and report that research is their primary or secondary work activity (i.e., the activity that occupies the most or second-most hours of their work time during a typical work week).[13] Estimates of this population come from NSF's biennial SDR.

There are several limitations associated with using the SDR to measure trends over time among academic research personnel. First, the survey excludes foreign-trained doctoral researchers, as well as researchers without a doctoral degree. Foreign-trained doctorate holders made up just under 20% of overall academic doctoral employees in 2010; they also figure very prominently in academic R&D.[14],[15] As a result, estimates in this analysis of the publications-to-researcher ratio are somewhat overstated, particularly in recent years. Furthermore, many students who have not yet received a doctorate conduct research that contributes to publications. In 2010, graduate research assistantships were the primary means of support for 27% of graduate students, a percentage that has remained fairly stable since the early 1990s.[16]

In defining academic R&D personnel as U.S.-trained, academically employed doctorate holders who report that research is their primary or secondary work activity, this analysis attempts to include persons who are most likely to be publishing articles. Further research could focus only on primary academic researchers—those who reported that research is their primary work activity. From 1993 to 2010, primary academic researchers represented a gradually growing share of academic researchers.[17] The SDR does not provide estimates of the number of hours researchers spend in their various work activities or how this number has changed over time; this could vary substantially over the years.

The fields component of this analysis assumes that academic researchers are conducting research in the area of their first doctorate in science, engineering, or health. Although this may be true for most academic researchers, it is not always the case. Additional analysis could explore field shifts from first doctoral degree for academic researchers.

Publication output, also referred to as "articles" or "article output," is measured by counts of S&E articles, notes, and reviews published in a set of scientific and technical journals tracked by Thomson Scientific in the Science Citation Index and Social Sciences Citation Index (http://www.thomsonreuters.com/business_units/scientific/).[18] Credit for articles is assigned to the institutions of the authors, not to the individual authors. Throughout the period of our analysis, roughly three-quarters of US publication output was produced by the academic sector.

Article output is allocated primarily by using "whole counts," which assign full credit for a publication to each category of institution that appears in an article's author list. For example, an article with one or more co-authors from both a public and a private university is counted once in the article count for public universities and once in the article count for private universities. Summing the counts for these two groups to arrive at an article count for all universities would result in the double-counting of articles collaborated between the groups. To improve upon whole counting, rather than summing articles this analysis counts each article only once in each aggregated group, regardless of collaboration. Because universities of different types often collaborate (e.g., Research I institutions collaborate with less research-extensive institutions and public universities collaborate with private universities), the whole counts of articles for universities as a group in these data are less than the sum of the whole counts for public universities and private universities. Similarly, whole counts of articles for universities as a group are also less than the sum of the whole counts for Research I and less research-extensive institutions.

Fractional counting, used to a lesser extent in this analysis, is an alternative method of measuring publication output.[19] In fractional counting, all publications receive a single credit. For collaborative publications, this credit is divided equally among the institutions credited in the list of the publication's authors. Because of the robust growth of academic R&D collaboration over the past 25 years, growth in article counts over time is more moderate when articles are counted fractionally than when they are counted using whole counts. The advantage to fractional counting is that groups can be aggregated by simple summing and no article will be counted more than once. For example, using fractional counting for an article that listed four institutional addresses—two different private U.S. universities, a French university, and a U.S. nonprofit institution—one-fourth of the publication would be attributed to each of the U.S. universities, one-fourth to the French university, and one-fourth to the U.S. nonprofit. With this method, the category of private universities would receive credit for one-half of an article.

As estimates, both whole and fractional counts are distortions. Whole counts give credit for the entire article to each participating institutional group under analysis as though that group had sole authorship, and fractional counts discount the extra effort that goes into combining contributions from different sources. Despite these differing distortions, both methods demonstrate the same basic pattern of an increasing expenditures-to-articles ratio over time and relatively flat trends over time in the ratio of articles to academic researchers. Thus, except where noted, all data presented is computed using whole counts.

Finally, conference proceedings, which are not well represented by Thomson Scientific in the Science Citation Index, play a significant role in certain fields, such as engineering and computer science. Thus, article counts for these fields may not reflect output as well as counts for other fields. The spending-to-publications ratio appears higher and the publications-to-researcher ratio appears lower than they would have been if conference proceedings were well represented in the publications database.

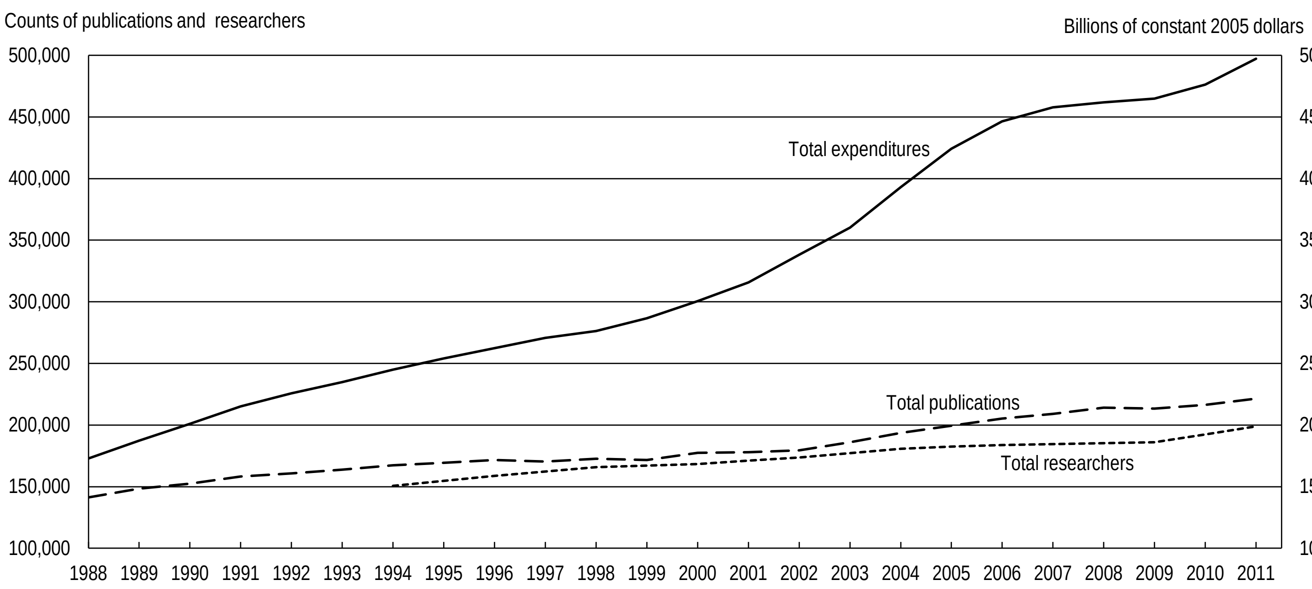
This analysis builds on previous NSF analyses of the publication output of the U.S. academic sector. Those previous analyses explored trends over a 15-year period from 1988 through 2003 in the total number of S&E publications whose authorship was credited to the U.S. academic sector.[20],[21],[22] Those analyses reported a leveling off of academic publication counts during the 1990s and early 2000s and examined possible contributing factors. Unlike those earlier studies, this paper is centrally concerned with trends in the relationship between resource inputs (R&D expenditures and academic researchers) and publication outputs. In addition, this paper covers a more recent period in which output again began to rise.

Findings

Researchers, Expenditures, and Publications within the Academic Sector

Although research funds, research personnel, and articles all increased within the academic sector from 1994 to 2011, they did so at markedly different rates (figure 1). After adjustment for inflation, academic S&E R&D expenditures doubled, rising from $24.5 billion to $49.7 billion. Meanwhile, academic research personnel and article counts grew more slowly, increasing by approximately 30% during the same period.[23]

FIGURE 1. Academic R&D publications, researchers, and expenditures: 1988–2011



NOTES: Whenever a year is noted, it refers to the publication year. Data for academic research personnel are lagged by one year, and data for R&D expenditures are lagged by two years, to account for the passage of time between funding, conducting, and publishing results of the research. Thus, the data shown in the figure for the estimated researchers in 1994 are actually 1993 estimates, and data shown in the figure for expenditures in 1988 are actually 1986 expenditures. Data on academic researchers prior to 1993 are not presented because data from 1988 to 1993 are not comparable to data from 1993 on. Total publications are computed using whole counts.

SOURCES: National Science Foundation, National Center for Science and Engineering Statistics, Survey of Research and Development Expenditures at Universities and Colleges and Survey of Doctorate Recipients; Patent Board analysis of Thomson Reuters Science Citation Index and Social Sciences Citation Index publications data.

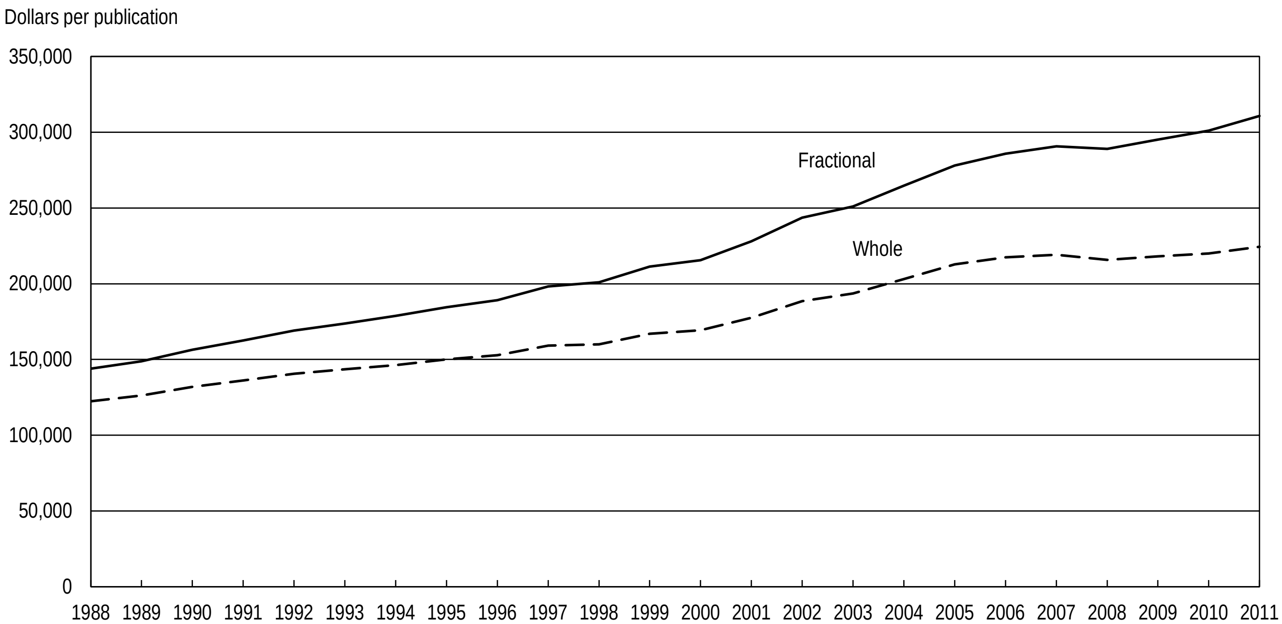
When the timeline is extended back to 1988, it becomes clear that the growth in expenditures varied over the full 23-year period. Average annual growth in expenditures was very strong from 1999 to 2006 at 7%, with 5% annual growth prior to that and 2% annual growth from 2007 to 2011.

Although both of the input factors are very good predictors of the article output, expenditures are more tightly coupled with article output than research personnel.

Overall Trends in the Ratios of Expenditures to Articles and Articles to Researcher

Over the period 1988–2011, there was a steady increase in the ratio of spending to S&E articles, regardless of the counting method used (figure 2). After adjustment for inflation, this ratio (using whole counts) increased by over 80% from 1988 to 2011 ($122,000 to $224,000). Growth rates were highest during the late 1990s and early 2000s, coinciding with the near-doubling of NIH’s budget. From 2006 to 2011, the spending-to-publications ratio was relatively stable, dipping slightly and then rising slightly.[24]

FIGURE 2. Ratios of academic R&D expenditures to publications: 1988–2011



NOTE: Constant 2005 dollars are used.

SOURCES: National Science Foundation, National Center for Science and Engineering Statistics, Survey of Research and Development Expenditures at Universities and Colleges; Patent Board analysis of Thomson Reuters Science Citation Index and Social Sciences Citation Index publications data.

Possible explanations for the increasing trend in the ratio of spending to publications through the mid-2000s are numerous. For one, research leading to publications may have become more complex and costly. For example, interdisciplinary research often requires extensive communication to synthesize different perspectives on a problem into a research project.[25] Or, in response to changing funding priorities, universities may have focused spending on activities and investments that did not necessarily result in publications. Another possible explanation could be that changes in university culture, specifically toward leadership that thinks increasingly in business terms, have resulted in a growing emphasis on converting research into patents.

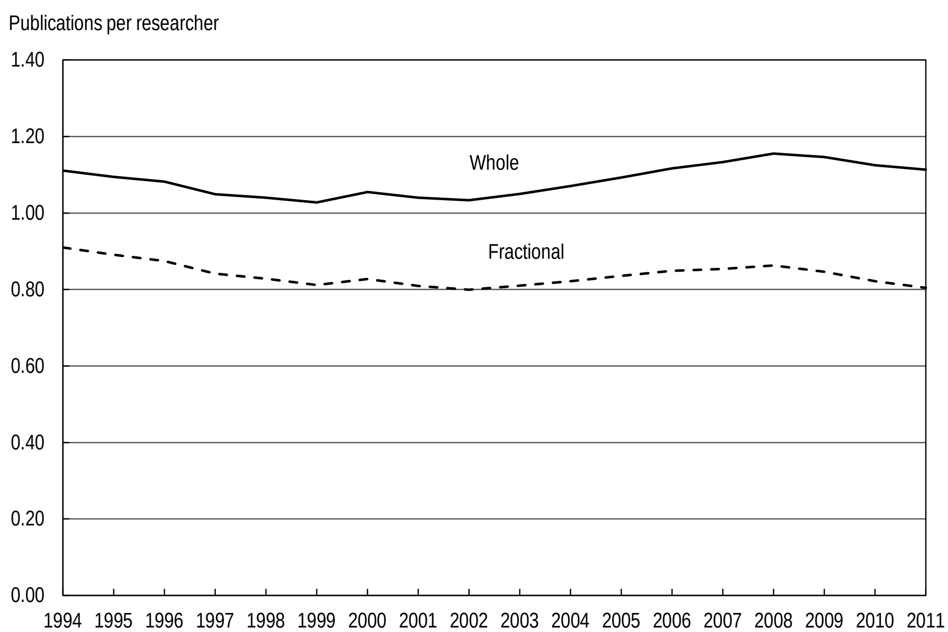
Changes in administrative responsibilities associated with conducting R&D may also have affected the spending ratio.[26] Survey results from the Federal Demonstration Partnership—a program sponsored by the National Academies to reduce administrative burdens associated with research grants and contracts—indicate that the percentage of time that federally funded principal investigators spend on administrative matters (excluding proposal writing) has more than doubled over the past two decades, rising from 18% in the early 1990s to 42% in 2010. Bienenstock suggests that a variety of factors may have contributed to this increase.[27]

- Changes in guidance from OMB Circular A-21 regarding the use of federal funds grants, contracts, and other agreements with educational institutions. The updated guidance limits the reimbursement of indirect administrative costs to 26% of the related direct costs for performing research. This change has caused universities to reduce the ranks of their administrative support personnel. As a result, higher-paid academic researchers spend more time completing administrative tasks that previously had been handled by lower-paid administrative support personnel.

- Increases in local and federal requirements associated with conducting research are often necessary to ensure safe, ethical research practices. However, these increased requirements place greater burdens on research faculty if universities do not provide additional administrative resources to aid in compliance.

- The growing emphasis on research in the life sciences over the past two decades[28] has led to increased administrative responsibilities, especially those associated with using humans and animals in experiments.[29]

FIGURE 3. Ratios of academic publications to researchers: 1994–2011



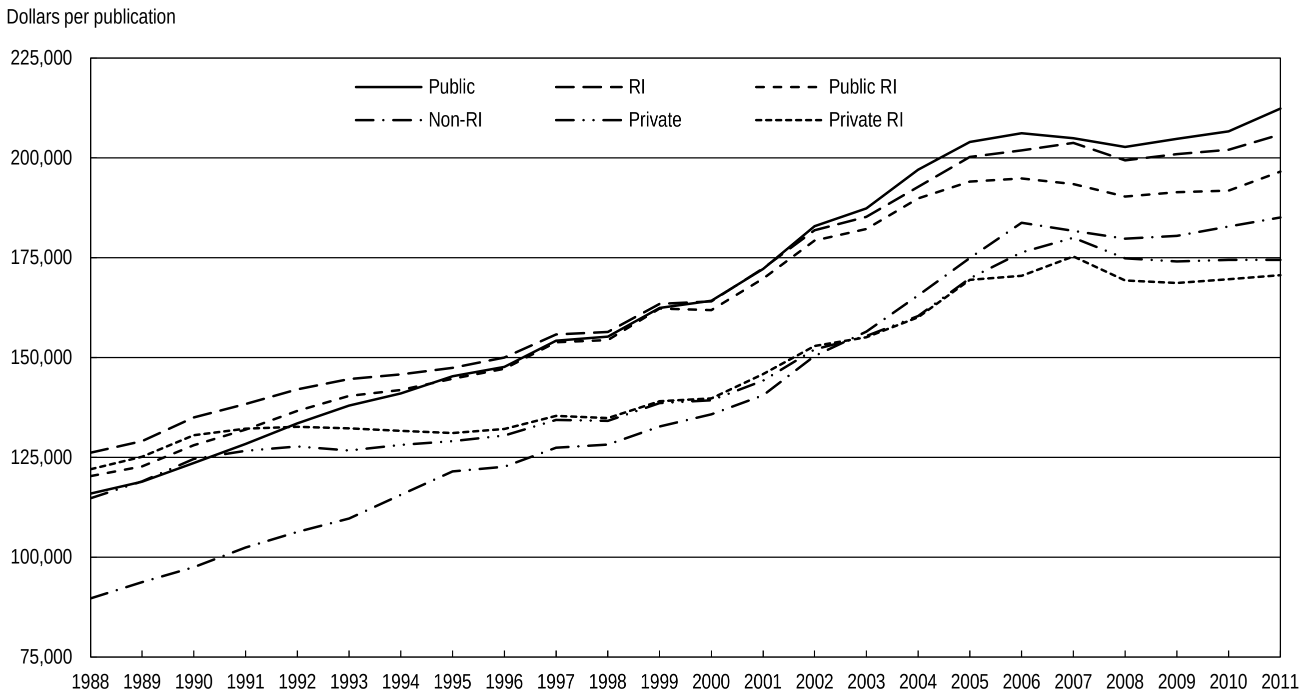
SOURCES: National Science Foundation, National Center for Science and Engineering Statistics, Survey of Doctorate Recipients; Patent Board analysis of Thomson Reuters Science Citation Index and Social Sciences Citation Index publications data.

The ratio of articles to academic researchers was relatively stable over the period of analysis. From 1994 to 2011, an average of about one article annually was associated with every researcher. From 1994 to 2002 there was a slight dip in the publications-to-researcher ratio. Output per researcher then grew steadily from 2003 to 2008, only to dip again slightly from 2009 to 2011. The relatively constant pattern over time was evident whether articles counts were computed using whole counts or fractional counts (figure 3).

Trends by University Type

The pattern of an increased academic R&D expenditures-to-publications ratio was replicated at all university types (figure 4). This ratio rose fastest at less research-extensive academic institutions (3.2% average annual increase). Increases were greater at public universities (2.7% average annual increase) than at their private counterparts (1.8% average annual increase). The gap in spending between public and private schools that appeared in the early 1990s has widened since then, with the spending-to-publications ratio being about the same for public and private schools in 1988, about $13,000 higher for public schools in 1994, and $38,000 higher for public schools in 2011. Unlike for public universities, in private schools the ratio of spending to articles produced was relatively stable throughout the 1990s. The lowest average annual increase was at the Research I private universities.

FIGURE 4. Ratios of academic R&D expenditures to publications, by university type: 1988–2011



RI = Research I university.

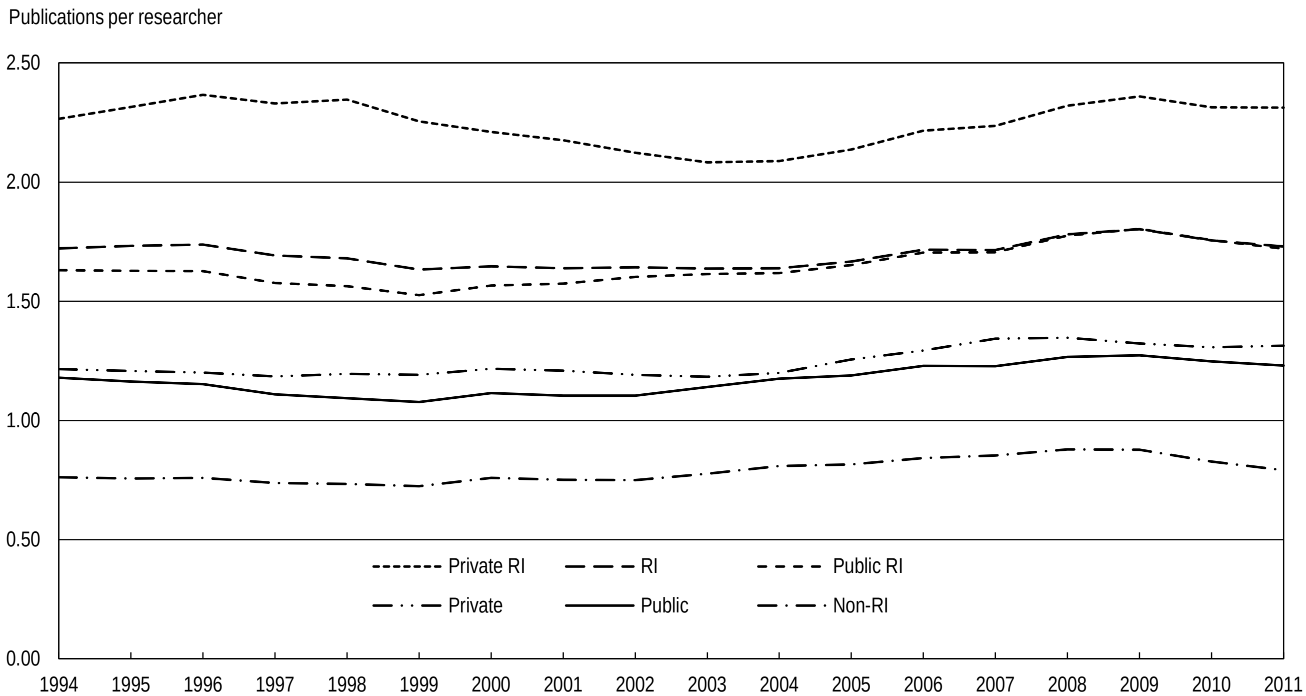
NOTE: Whole article counts and constant 2005 dollars are used.

SOURCES: National Science Foundation, National Center for Science and Engineering Statistics, Survey of Research and Development Expenditures at Universities and College, special tabulations; Patent Board analysis of Thomson Reuters Science Citation Index and Social Sciences Citation Index publications data.

In general, private universities and colleges have only a slightly higher publications-to-researcher ratio than their public counterparts, but among the most research-extensive academic institutions, the difference is somewhat greater (figure 5). This could reflect greater focus at private institutions on publishing, as well as the broader missions of public institutions. The nation's Research I institutions were credited with over twice as many publications as less research-extensive institutions. Trends in publication rates are relatively flat for most university types but show an increase from 2004 to 2009. The greatest fluctuation over the period was for the nation's Research I private institutions, which dropped from 2.4 articles in 1998 to 2.1 in 2003 before rising back up to 2.4 again by 2009.

This increase in publication rates during the 2000s throughout the academic sector likely reflects the near-doubling of the National Institutes of Health's (NIH's) research budget between 1998 and 2003; during the middle years of the 2000s, academic researchers in the life sciences would have completed and begun to report the results of research paid for by grants resulting from NIH's increased research budget.[30] With the life sciences constituting well over 50% of total academic R&D expenditures, any changes affecting NIH's research budget have a corresponding effect on total academic R&D.

FIGURE 5. Ratios of academic publications to researchers, by university type: 1994–2011



RI = Research I university.

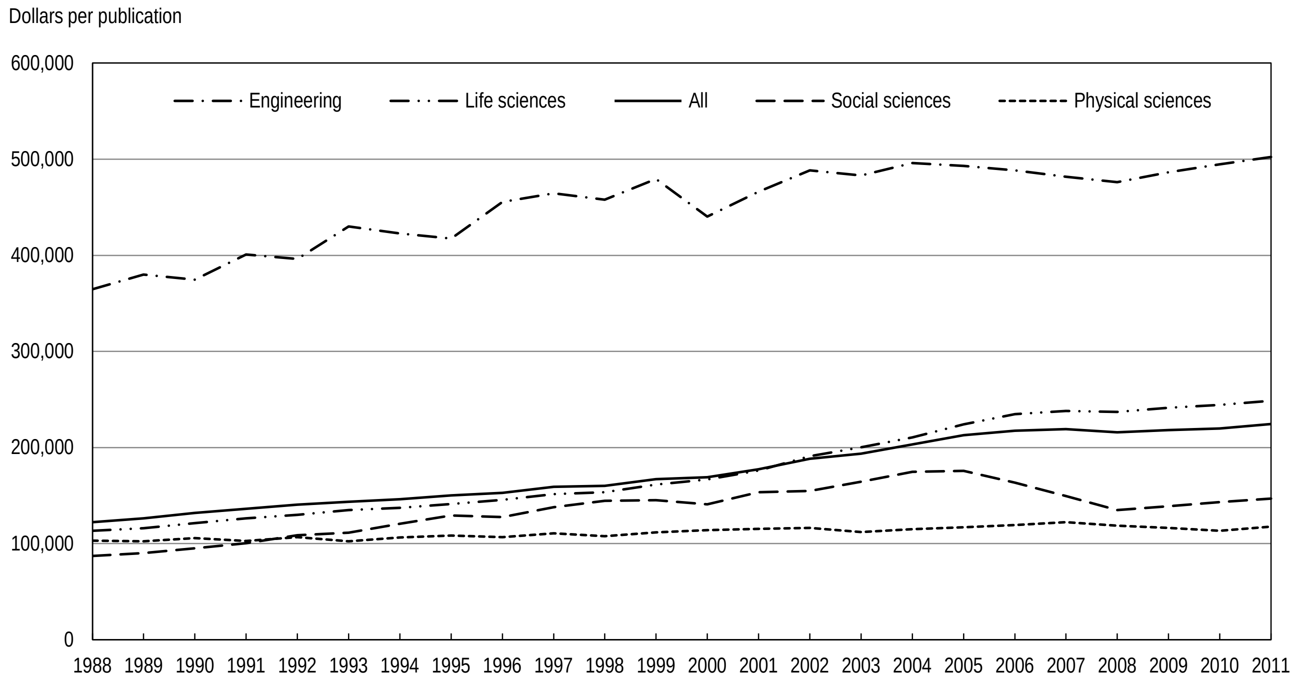
NOTE: Whole article counts are used.

SOURCES: National Science Foundation, National Center for Science and Engineering Statistics, Survey of Doctorate Recipients; Patent Board analysis of Thomson Reuters Science Citation Index and Social Sciences Citation Index publications data.

Trends by Broad Field

Publication practices vary across the various S&E fields. For example, social sciences researchers tend to publish fewer journal articles and more books than do researchers in health sciences. Also, in the data under analysis there are ten times as many life science articles than social sciences articles but only twice as many researchers. Because of these field differences, aggregate comparisons across all fields of S&E of the publications-to-researcher ratio are affected when universities specialize in certain fields. Similarly, field differences can also complicate comparisons across fields in the spending-to-publications ratio. Fields requiring more sophisticated research equipment require greater expenditures. Thus it is important to look at trends within individual fields. Aggregate academic sector trends over time were not replicated at the level of each broad S&E field (figure 6).[31]

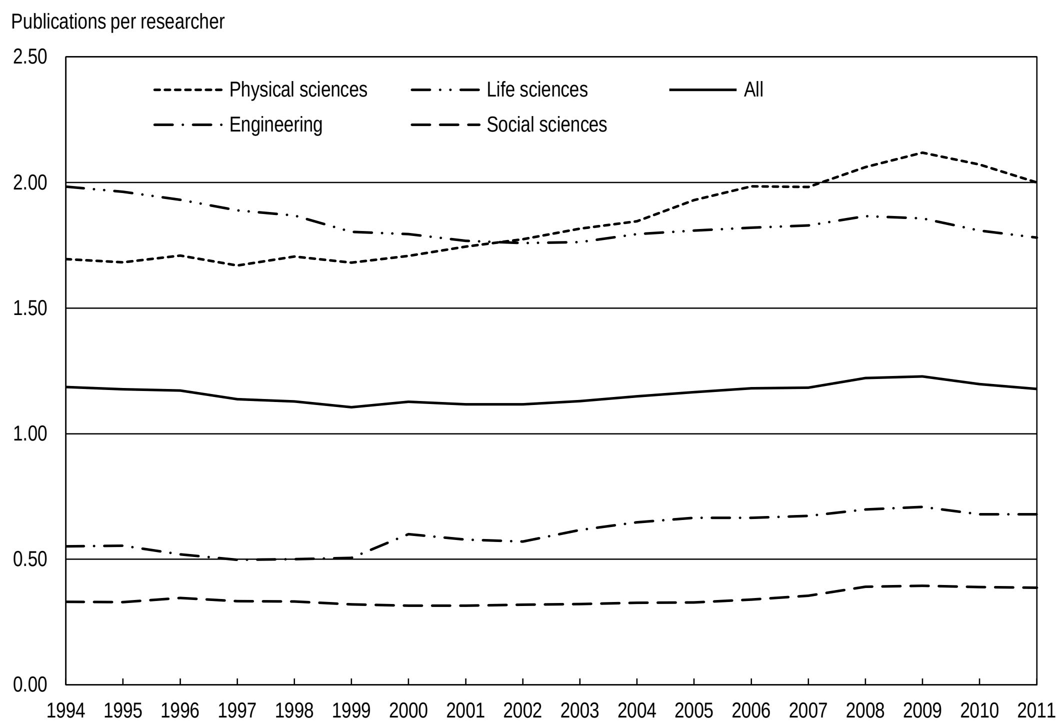
FIGURE 6. Ratios of academic R&D expenditures to publications, by major field: 1988–2011



NOTE: Whole article counts and constant 2005 dollars are used.

SOURCES: National Science Foundation, National Center for Science and Engineering Statistics, Survey of Research and Development Expenditures at Universities and Colleges, special tabulations; Patent Board analysis of Thomson Reuters Science Citation Index and Social Sciences Citation Index publications data.

FIGURE 7. Ratios of academic publications to researchers, by major field: 1994–2011



NOTE: Whole article counts are used.

SOURCES: National Science Foundation, National Center for Science and Engineering Statistics, Survey of Doctorate Recipients; Patent Board analysis of Thomson Reuters Science Citation Index and Social Sciences Citation Index publications data.

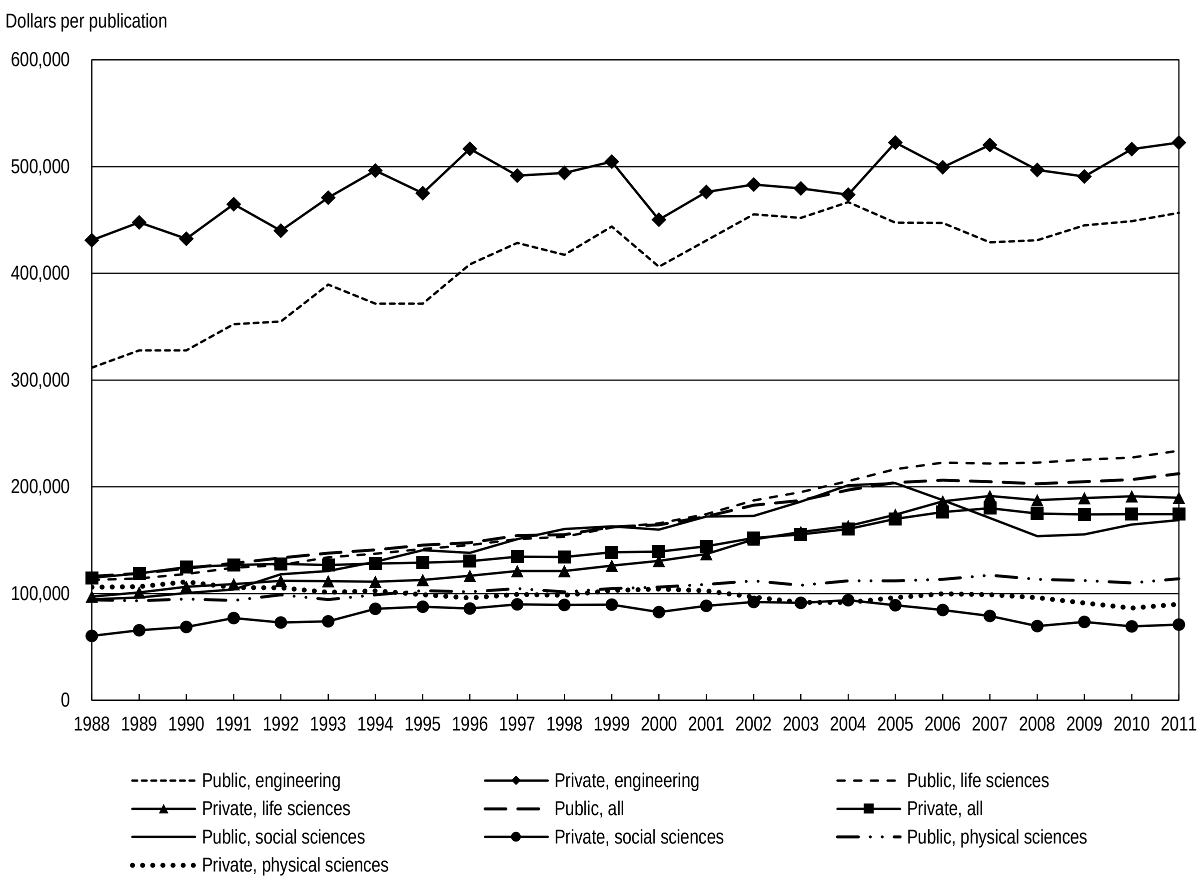
Trends in life sciences publishing, making up the majority of academic publishing, mirrored trends for the academic sector as a whole throughout most of the time period. The percentage increases in the spending-to-publications ratio from 1988 to 2011 were highest in life sciences (120%), followed by social sciences (just under 70%) then engineering (just under 40%). The spending ratio in physical sciences remained relatively flat (less than 15% increase).[32]

Interesting differences exist by field in the relationships between academic researchers and publication counts over time. The ratio of publications to researchers rose in the physical sciences and somewhat in engineering, remained fairly stable in the social sciences, and decreased slightly in the life sciences (figure 7).[33]

Trends by University Type and Field

As already discussed, public universities and colleges had a higher spending-to-publications ratio than their private counterparts (figure 4). This is true for each of the broad fields except for engineering, where private institutions had a higher spending ratio but less growth over the past 15 years (figure 8).

FIGURE 8. Ratios of academic R&D expenditures to publications, by major field and institutional control: 1988–2011



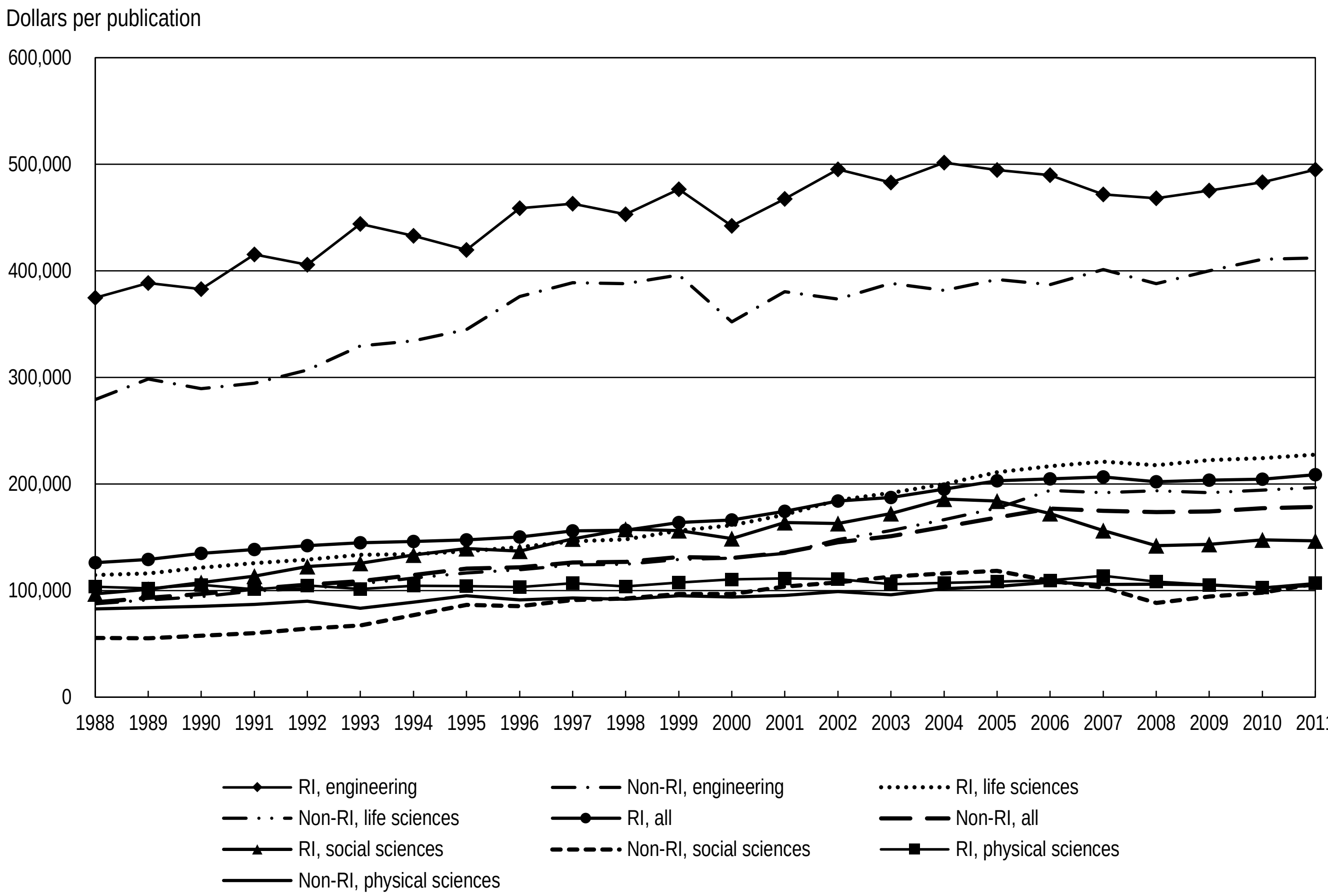
NOTE: Whole article counts and constant 2005 dollars are used.

SOURCES: National Science Foundation, National Center for Science and Engineering Statistics, Survey of Research and Development Expenditures at Universities and Colleges, special tabulations; Patent Board analysis of Thomson Reuters Science Citation Index and Social Sciences Citation Index publications data.

Also, with the exception of engineering, public schools showed similar spending-to-publication ratios in each field during the first few years of this analysis. The spending-to-publications ratio in the physical sciences varied somewhat between public and private institutions. It increased very slightly at public universities and colleges while dropping somewhat at their private counterparts. From the late 1990s through 2005, this ratio for social sciences publications grew rapidly at public schools while showing essentially no change at private schools.

In every broad field, the spending-to-publications ratio was generally higher for Research I institutions than for less research-extensive institutions (figure 9). The trend in each field and institution type was toward an increasing spending ratio. The one exception was physical sciences in Research I institutions, where the spending to publications ratio held steady throughout the period.

FIGURE 9. Ratios of academic R&D expenditures to publications, by major field and university type: 1988–2011



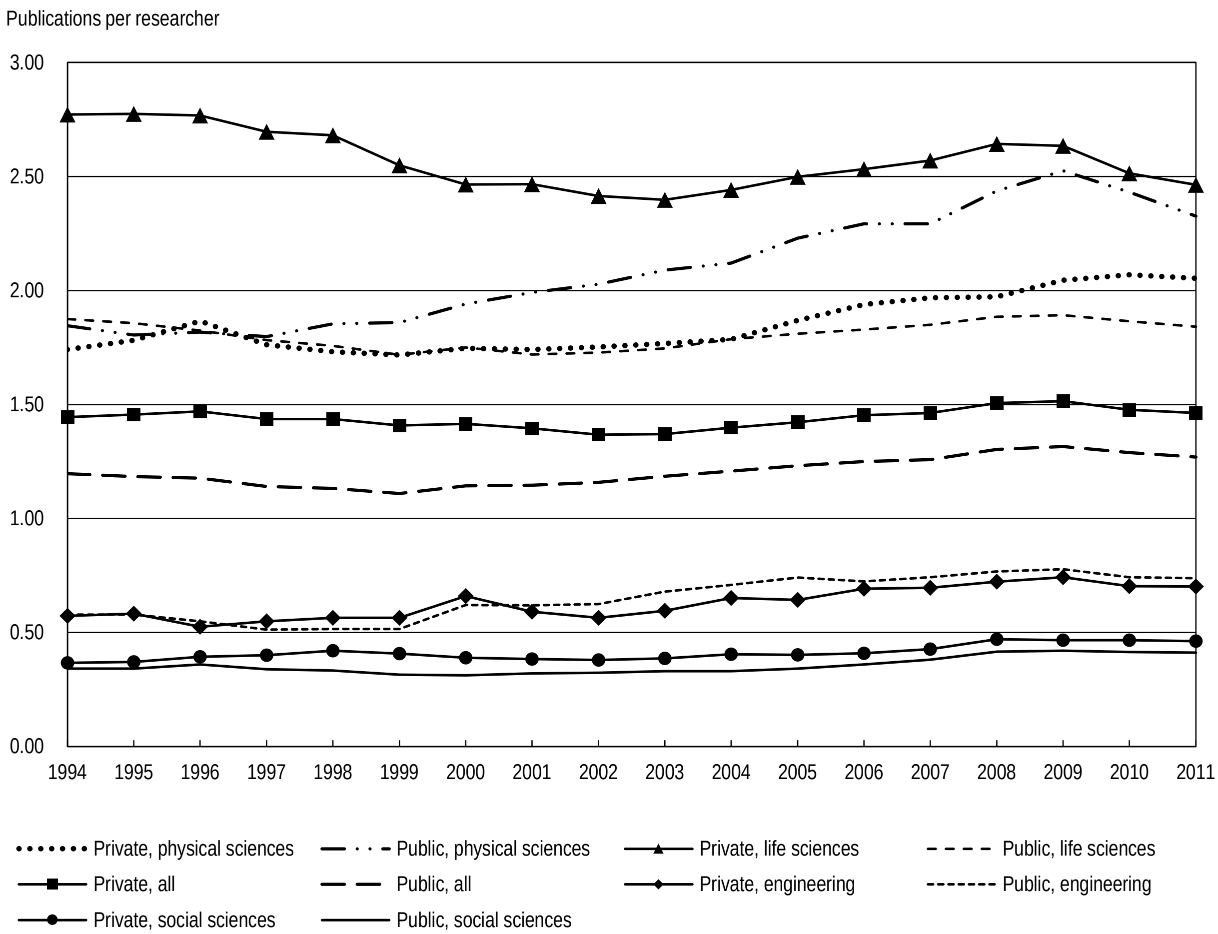
RI = Research I universities.

NOTES: Whole article counts and constant 2005 dollars are used.

SOURCES: National Science Foundation, National Center for Science and Engineering Statistics, Survey of Research and Development Expenditures at Universities and Colleges, special tabulations; Patent Board analysis of Thomson Reuters Science Citation Index and Social Sciences Citation Index publications data.

As previously stated, the publications-to-researcher ratio was highest in the physical and life sciences; however this ratio was rising in the physical sciences and falling in the life sciences (figure 7). This falling ratio in the life sciences is attributable mainly to private and Research I universities and colleges, both of which dropped by 0.3 publications per researcher over the time period, while rates for public and less research-extensive institutions changed very little from the beginning to the end of the period (figures 10 and 11).

FIGURE 10. Ratios of academic publications to researchers, by major field and institutional control: 1994–2011

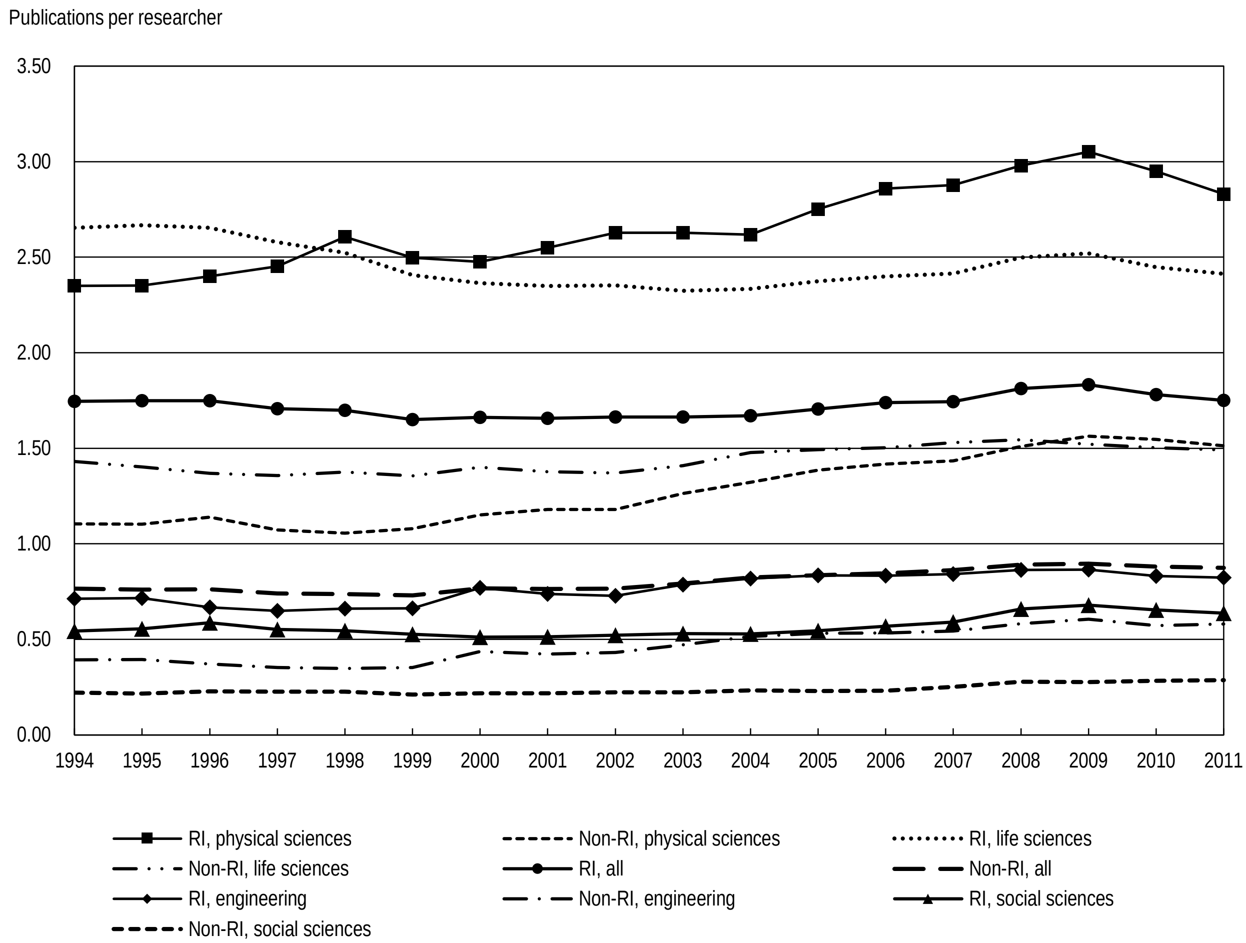


NOTE: Whole article counts are used.

SOURCES: National Science Foundation, National Center for Science and Engineering Statistics, Survey of Doctorate Recipients; Patent Board analysis of Thomson Reuters Science Citation Index and Social Sciences Citation Index publications data.

Although the publications-to-researcher ratio in physical sciences has surpassed that in the life sciences for public and Research I institutions, this crossover has yet to occur for private institutions and only recently occurred for less research-extensive schools. Further research is needed to explore the dynamics affecting life sciences and physical sciences R&D in public and private universities. For the two remaining broad fields, engineering and social sciences, institution type has little impact on publication rates—rates and trends are nearly identical for public and private universities and colleges.

FIGURE 11. Ratios of academic publications to researchers, by major field and university type: 1994–2011



RI = Research I universities.

NOTES: Whole article counts are used. Fields refer to the fields of first doctorate in science, engineering, or health.

SOURCES: National Science Foundation, National Center for Science and Engineering Statistics, Survey of Doctorate Recipients; Patent Board analysis of Thomson Reuters Science Citation Index and Social Sciences Citation Index publications data.

Conclusions and Suggestions for Further Study

From 1988 to 2006, the ratio of academic R&D spending to publications increased regardless of counting method used; however, this trend was not evident from 2007 to 2009. From 2009 to 2011, this ratio began to increase again. Although the increase was evident at all institution types, the rate of growth was highest for less research-extensive universities and for public schools. Private schools, especially those that are Research I institutions, showed very little or no growth in the spending-to-publications ratio from 1991 to 1996.

Using whole counts, the ratio of articles to academic researchers increased during the first two-thirds of the 2000s. However, from 2007 to 2011, this ratio gradually declined to the 1994 level. When publications are counted fractionally, there was a slight decrease in the average annual per capita output of publications from 1994 to 2011. Neither estimate takes into consideration academic researchers who received their doctorate overseas. Finally, it appears that the relative flattening of annual academic S&E publication output during the 1990s and early 2000s has ended (figure 1).

This analysis focused on academic researchers whose primary or whose primary or secondary work responsibility was R&D. Further study focused more narrowly on primary academic researchers would be beneficial. For example, a more detailed analysis of the work activities over time of primary academic researchers at private and at public universities and colleges could shed light on the extent to which these researchers are being called upon to take on more administrative or other responsibilities that do not result in publications.

Throughout the quarter century covered in this analysis, many factors have contributed to trends in academic S&E publication output. As this paper notes, one of the most important factors is the increasingly collaborative nature of academic R&D. This growing collaboration is reflected by downward trends in the number of articles counted fractionally per researcher, and analyses focusing on finding ways to measure the relative contribution of various institutions or individuals to articles in specific S&E fields could shed more light on this phenomenon.[34]

Further analysis of changes in the research process, both by and across fields, could explore and potentially begin to measure the extent to which academic R&D is becoming more complex, involving time-consuming integration of diverse perspectives to address multifaceted research problems. For example, it would be helpful to analyze what fields are most prominently represented in interdisciplinary research and the impact this could have on spending per publication. Studies could explore ways to quantify the movement over the past two decades toward more integrative collaborations and how this has affected academic S&E publication patterns.

More research might clarify how and to what extent administrative responsibilities associated with academic R&D affect academic publications output. For example, research could measure whether and how much the life sciences are disproportionately affected by growing administrative responsibilities. Differences in research practices between public and private universities and colleges and between the nation’s Research I institutions and others are also potentially fruitful topics. Finally, additional analysis could focus on the effect of changes in publication practices, by field and at the academic sector level.

Notes

1. Katherine Hale, Science and Engineering Indicators Program, National Center for Science and Engineering Statistics, National Science Foundation, 4201 Wilson Boulevard, Suite 965, Arlington, VA 22230 (khale@nsf.gov; 703-292-7786). Kimberly Hamilton, formerly with The Patent Board, Westmont, New Jersey.

2. All dollar values listed in this paper are adjusted to constant 2005 dollars using the GDP deflator.

3. The Carnegie classification of institutions of higher education is widely used in higher education research to characterize and control for differences among academic institutions. The 1994 classification includes six broad categories of institutions, including doctorate-granting research universities, master's colleges and universities, baccalaureate colleges, associate's colleges, specialized institutions, and tribal colleges and universities. Among doctorate-granting research universities, institutions with the highest level of research activity are designated as Research I universities in the 1994 classification.

4. Because of changes in the survey questionnaire about work activities, data prior to 1993 are not directly comparable to data from 1993 and afterward. As a result, this analysis draws data from the SDR in the nine survey cycles spanning 1993–2010 (data for intervening years are interpolated by applying the annual growth rate computed using the two surrounding years to the missing years).

5. This is unsurprising given that about two-thirds of the nation's top 100 institutions in S&E R&D expenditures are publicly controlled. See National Science Board (NSB). 2014. Science and Engineering Indicators 2014, appendix table 5-6. NSB 14-01. Arlington, VA: National Science Foundation. Available at http://www.nsf.gov/statistics/seind14/.

6. This paper grouped publications and expenditures data as closely as possible to the fields of researchers' first doctorate in science, engineering, or health. Included in the overall totals but not separately analyzed are computer sciences, mathematics, and psychology.

7. This method was selected because an earlier NSF analysis generally showed that publications in a given year were most closely linked to personnel counts from the previous year and to expenditures from two years before the publication year; an alternate way yielding very similar results would be to have a two-year lag between both expenditures and publications and personnel counts and publications. Whenever a year is noted in the text, figures, or tables, it refers to the publication year. See Javitz H, Grimes T, Hill D, Rapoport A, Bell R, Fecso R, and Lehming R. 2010. U.S. Academic Scientific Publishing. Working Paper SRS 11-201. Arlington, VA: National Science Foundation, Division of Science Resources Statistics. Available at http://www.nsf.gov/statistics/srs11201/.

8. This analysis does not count spending by non-U.S. academic co-authoring institutions. If included, estimates of spending per publication would be somewhat higher, especially in recent years.

9. See National Science Foundation, National Center for Science and Engineering Statistics. 2011. Academic Research and Development Expenditures: Fiscal Year 2009. Detailed Statistical Tables NSF 11-313. Arlington, VA. Available at http://www.nsf.gov/statistics/nsf11313/.

10. Britt R. 2012. Overview of FY 2010 findings from NSF's Higher Education R&D Survey. Presentation at the 2012 American Institutes for Research (AIR) Annual Forum, Washington, DC, 5 June.

11. Indirect costs are general expenses that cannot be associated with specific research projects but pay for things that are used collectively by many research projects at an academic institution. Two major components of indirect costs exist: (1) facilities-related costs, such as the construction, maintenance, and operation of facilities used for research and (2) administrative costs, including expenses associated with financial management, institutional review boards, and environment, health, and safety management.

12. In this analysis, health doctorates are grouped with doctorates in biological, agricultural, and environmental life sciences to create the broad field of life sciences.

13. In this analysis, research includes basic research, applied research, development, and design.

14. In 2010, the U.S.-trained academic workforce with doctorates in science, engineering, or health numbered about 295,000, whereas their foreign-trained counterparts numbered about 64,000. About 90% of the nation's foreign-trained academic doctoral personnel classified research as their primary or secondary work activity as compared to about 70% of their U.S.-trained counterparts.

15. National Science Board (NSB). 2014. Science and Engineering Indicators 2014, chapter 5. Arlington, VA: National Science Foundation. Available at http://www.nsf.gov/statistics/seind14/. See pages 5-24 and 5-61.

16. National Science Board (NSB). 2014. Science and Engineering Indicators 2014, chapter 5. Arlington, VA: National Science Foundation. Available at http://www.nsf.gov/statistics/seind14/. See page 5-32.

17. National Science Board (NSB). 2014. Science and Engineering Indicators 2014, chapter 5. Arlington, VA: National Science Foundation. Available at http://www.nsf.gov/statistics/seind14/. See page 5-30 and appendix table 5-19.

18. The changing set of journals reflects the current mix of the world's influential journals. Article count excludes letters to the editor, news stories, editorials, and other material whose purpose was not the presentation or discussion of scientific data, theory, methods, apparatus, or experiments. Thomson Reuters selects journals each year as described at http://www.thomsonreuters.com/products_services/science/free/essays/journal_selection_process/. The journals selected are notable for their relatively high citation rank within their corresponding S&E subfields; journals of only regional interest are excluded. The set of journals covered in this working paper—covering the analyzed fields—grew at an average annual rate of 1%, from 3,587 in 1988 to 4,437 in 2011.

19. Publication counts reported in the National Science Board's biennial *Science and Engineering Indicators* reports are typically counted on a fractional basis, allowing for an approximation of the share of the contribution of each country (or institutional sector) toward the whole paper because every individual institutional address on a publication is given an equal share. For example, a paper with three French and one U.S. institutional address is attributed three-fourths to France and one-fourth to the U.S. when counting fractionally, but it is attributed one count to each country when using whole counts. Fractional counting minimizes over-crediting to a country a paper where the majority of the coauthors are from another country (or institutional sector).

20. Javitz H, Hill D, Rapoport A, Bell R, Fecso R, and Lehming R. 2010. U.S. Academic Scientific Publishing. Working Paper SRS 11-201. Arlington, VA: National Science Foundation, Division of Science Resources Statistics. Available at http://www.nsf.gov/statistics/srs11201/. This working paper analyzes the covariates of publication trends in the nation's top 200 R&D performing universities and

includes an analysis of the effects of different assumptions about the lag times between research activity and publications.

21. Hill D, Rapoport AI, Lehming RF, and Bell RK. 2007. Changing U.S. Output of Scientific Articles: 1988–2003. Working Paper NSF 07-320. Arlington, VA: National Science Foundation, Division of Science Resources Statistics. Available at http://www.nsf.gov/statistics/nsf07320/. This special report delineates national and international trends in publication and coauthorship. In a section on methodological issues it discusses the journal database and alternate methods for counting publications.

22. Bell RK, with Hill D and Lehming RF. 2007. The Changing Research and Publication Environment in American Research Universities. Working Paper SRS 07-204. Arlington, VA: National Science Foundation, Division of Science Resources Statistics. Available at http://www.nsf.gov/statistics/srs07204/. This working paper records the perspectives of academic scientists and administrators on the changing research and publication environment in U.S. universities.

23. Estimates of personnel growth rates were somewhat higher from 1994 to 2011 (just over 40%) for the smaller set of academic researchers whose primary responsibility was to conduct research.

24. Higher rates and somewhat greater growth in recent years for fractional counts can be attributed to the trend toward increasing collaboration; recall that fractional counting credits only a portion of each coauthored article to each participating institution.

25. See Newell WH, 2007. Decision-making in interdisciplinary studies. *In* Morcol G, editor, *Handbook of Decision Making.* Boca Raton, FL: CRC Press.

26. See National Science Board (NSB). 2014. Reducing Investigators' Administrative Workload for Federally Funded Research. NSB 14-18. Arlington, VA: National Science Foundation. Available at http://nsf.gov/pubs/2014/nsb1418/nsb1418.pdf.

27. Bienenstock A. 2009. Administrative burdens stifle faculty and erode university resources. APS News. http://www.aps.org/publications/apsnews/200907/backpage.cfm/.

28. NIH's share of total federal obligations for academic R&D grew by 10 percentage points in the 20-year period spanning 1989–2009, rising from 54% in 1989 to 64% in 2009.

29. Bienenstock A. 2009. Administrative burdens stifle faculty and erode university resources. APS News. http://www.aps.org/publications/apsnews/200907/backpage.cfm/.

30. There was a 10% increase in life sciences publications from 2000 to 2005, likely reflecting the increase in NIH's budget. For the 5-year period prior to 2000 (1994 to 1999), life sciences publications increased by 2%.

31. See Rosenbloom JL, Ginther DK, Juhl T, and Heppert J. The Effects of Research and Development Funding on Scientific Productivity: Academic Chemistry, 1990–2009. Working Paper 20595. Cambridge, MA: National Bureau of Economic Research. Available at http://www.nber.org/papers/w20595. This paper analyzes trends in the relationship between spending in chemistry (including spending in chemical engineering) and publications and finds that spending per publication decreased over time. The paper also reports less spending per publication at the nation's Research I universities than at the other institutions it covers. These findings differ from those in our analysis. Two important differences in methodology are (1) National Bureau of Economic Research (NBER) limited their analysis to a subset of about 150 universities and colleges that received the most federal R&D funding over the period 1990–2009, and (2) NBER's publications data set added many

journals over time. In addition, NBER did not attempt to control for growing academic R&D collaboration over time.

32. The expenditures-to-publications ratio for social sciences increased until around 2005, when this spending dropped sharply until 2008 and then leveled off. The data sources used in this analysis do not illuminate this atypical pattern involving the social sciences. One explanation may be that Thomson Scientific added an unusually large number of social sciences journals to their Social Sciences Citation Index coverage in 2008. In ensuing years, Thomson dropped many of the newly added journals.

33. Trends were generally similar using fractional counts.

34. Beginning in 1995 (and periodically thereafter), the SDR has collected limited information on publication and patenting activity among respondents. To improve understanding of the products of research among U.S.-trained science, engineering, and health doctorates, NCSES has undertaken a project to link the SDR data files to several major publication and patent databases. This will provide direct measures of publication activities of SDR respondents and enable further analysis of factors related to publication and patent outputs. Data files will be available by license.