Scientific publications at U.S. federal research laboratories

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Abstract:

In this paper, we focus on scientific publications as an innovative output from the research efforts at U.S. federal laboratories. The data used relate to Federally Funded Research and Development Centers (FFRDCs). The relationship between R&D expenditures at these federal laboratories and their peer-reviewed scientific publications allows us to make inferences about the return to public-sector R&D. We examine two complementary statistical models. From the first model, we find that a 10% increase in constant dollar public-sector R&D is associated with between a 15.5 and 21.5% increase in scientific publications. From the second model, we find that the annual rate of return generated by an additional $1 million of R&D-based knowledge stock varies across the FFRDCs, averaging about 93 additional scientific publications, with the statistically significant values ranging from about 1 to as many as about 400 additional scientific publications.

Keywords: scientific publications | federal laboratory | R&D | Evaluation | return on investment

Article:

Introduction

President Donald J. Trump's *The President's Management Agenda: Modernizing Government for the 21st Century* (undated, p. 1) sets forth "a long-term vision for modernizing the Federal Government in key areas that will improve the ability of agencies to deliver mission outcomes, provide excellent service, and effectively steward taxpayer dollars on behalf of the American people."[1] The "long-term vision" is encapsulated by 14 Cross-Agency Priority (CAP) Goals that identify areas in which "agencies collaborate to effect change and report progress in a manner the public can easily track" (p. 9).

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[1] The original version of *The President's Management Agenda* is undated; however, online it is referred to as the 2018 version. There have been two updates since the 2018 version.

CAP Goal 14: Improve Transfer of Federally-Funded Technologies from Lab-to-Market is relevant to the theme of this paper. CAP Goal 14 in *The President's Management Agenda* states (p. 47):

> The Federal Government invests approximately $150 billion annually in research and development (R&D) conducted at Federal laboratories, universities, and other research organizations. For America to maintain its position as the leader in global innovation, bring products to market more quickly, grow the economy, and maintain a strong national security innovation base, it is essential to optimize *technology transfer* [emphasis added] and support programs to increase the return on investment (ROI) from federally funded R&D.

The federal laboratory technology transfer emphasis of CAP Goal 14 is arguably a follow-on to the thematic emphasis of President Barack Obama's (2011) *Presidential Memorandum—Accelerating Technology Transfer and Commercialization of Federal Research Support of High Growth Businesses* in which it is written:

> I direct that [Federal laboratories] establish goals and measure performance, streamline administrative processes, and facilitate local and regional partnerships in order to accelerate technology transfer and support private sector commercialization.

Several recent research papers have been motivated by CAP Goal 14, and the authors have approximated an estimate of the returns to federal laboratory R&D in terms of an estimate of an innovation output elasticity of public-sector R&D using federal agency—not federal laboratory—data. This literature has focused on patent applications as the relevant innovation output measure to correlate with public-sector R&D investments.[2] Researchers' choice for the use of patent applications might be due to the availability of data as well as to patents being a widely accepted vehicle (i.e., a technology transfer mechanism) through which new technology enters society.

In this paper, we revisit the innovation output elasticity of public-sector R&D using laboratory-specific data, and we introduce peer-reviewed scientific publications as a relevant innovation output measure through which public-sector R&D-based knowledge enters society. Thus, the contribution of this paper is not only to provide information relevant to a return to R&D metric using federal laboratory data but also to emphasize that scientific publications are a relevant, and somewhat overlooked, innovation output from research in federal laboratories.[3] More specifically, the U.S. technology transfer literature has primarily focused on patents, patent

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[2] See Link, Morris, and Van Hasselt (2019), Link and Van Hasselt (2019), and Link and Oliver (2020). Overall, these publications report that a 10% increase in federal agency per capita R&D is associated with more than a 10% increase in new patent applications by the funding agencies.

[3] Link and Scott (2019, 2020) have studied scientific publications at one U.S. federal laboratory, the National Institute of Standards and Technology (NIST). They found evidence that the return on investments of public-sector R&D has declined in the sense that, as time has progressed, more public-sector R&D is required to produce scientific publications. Relatedly, Audretsch et al. (2019) studied scientific publications resulting from public-sector R&D allocated to private-sector firms through the Small Business Innovation Research (SBIR) program. These authors found that a 10% increase in an SBIR project's budget corresponds to an 11% increase in the number of scientific papers submitted for publication.

licenses, and CRADAs (cooperative research and development agreements) even though, as emphasized in “Scientific publications as an innovation output” section, the primary vehicle or channel for transferring federal research results is through scientific publications.[4] This paper represents the first broad-based study of technology transfer, albeit it only though scientific publications, at the laboratory level.

In the following “Scientific publications as an innovation output” section, we offer a more systematic justification for our focus on scientific publications as a relevant innovation output from federal laboratories, and we describe the federal laboratories from which the scientific publication data studied herein were collected—Federally Funded Research and Development Centers (FFRDCs).

In “Analytical analysis and estimates of scientific publication elasticity” section, we present empirical estimates of the output elasticity of scientific publications with respect to federal laboratory R&D expenditures, and we discuss how our findings might be interpreted from a policy perspective. We follow the econometric methodology of previous researchers who studied patents as the relevant R&D output metric, but our method of analysis is based on a single variable publication knowledge production function.

In “A rate of return on R&D knowledge capital” section, we present an alternative yet complementary way of examining our data. We present empirical estimates of the rate of return to investments in federal laboratory knowledge capital, and our results are compared with the elasticity results from the preceding section.

“Concluding remarks” section concludes the paper with summary remarks, a discussion of the complementary interpretation of the metrics from the two models presented in “Analytical analysis and estimates of scientific publication elasticity” and “A rate of return on R&D knowledge capital” sections, and suggestions for a possible agenda for future research.

Scientific publications as an innovation output

An emphasis on technology transfer from federal laboratories might reasonably be traced to Vannevar Bush’s June 5, 1945 report to President Harry S. Truman, *Science—the Endless Frontier.*[5] In the transmittal letter of his report, Bush wrote (1945, p. 2):

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[4] Data on patents, licenses, and CRADAs are readily available at the agency level through the Technology Partnerships Office (TPO) at the National Institute of Standards and Technology (NIST), but federal laboratories have historically been reluctant to make public their data on technology transfer activities. This remains the case even in light of President Obama’s (2011) Memorandum as documented by Link and Oliver (2020). The Board on Science and Technology Policy (STEP) at the National Academies (the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine) recently commissioned a study on Advancing Commercialization from the Federal Laboratories. Their draft report to the U.S. Congress calls for greater transparency by federal laboratories about their technology transfer activities. See https://www.nationalacademies.org/our-work/advancing-commercialization-from-the-federal-laboratories.

[5] President Franklin D. Roosevelt commissioned the report from Bush on November 17, 1944, but he passed away on April 12, 1945.

> The pioneer spirit is still vigorous within this nation. Science offers a largely unexplored hinterland for the pioneer who has the tools for his task. The rewards of such exploration both for the Nation and the individual are great. Scientific progress is one essential key to our security as a nation, to our better health, to more jobs, to a higher standard of living, and to our cultural progress.

Implicit in the above passage from Bush to President Truman is that the transfer of scientific knowledge, emanating from public-sector funded research (and thus from public-sector R&D), is a foundation for the future development of new technologies for the betterment of our nation.

More recently, the Stevenson-Wydler Act of 1980 formalized a policy emphasis on technology transfer activities in federal laboratories:[6,7]

> Technology and industrial innovation are central to the economic, environmental, and social well-being of citizens of the United States … It is the purpose of this Act to improve the economic, environmental, and social well-being of the United States by … promoting technology development through the establishment of centers for industrial technology [within Federal laboratories and] stimulating improved utilization of federally funded technology developments …

The Stevenson-Wydler Act was amended by the Federal Technology Transfer Act of 1986. The 1986 Act—along with President Ronald W. Reagan's April 10, 1987 Executive Order 12591, Facilitating Access to Science and Technology—mandated that the Office of Technology Policy within the Technology Administration of the Department of Commerce (DOC) submit to Congress biannual reports on technology transfer activities in the laboratories of federal agencies. Under the Technology Transfer Commercialization Act of 2000, these reports are now prepared and submitted to the President and the Congress annually through the Technology Partnerships Office (TPO) at the National Institute of Standards and Technology (NIST) within the DOC[8]:

> Each Federal agency … shall report annually to the Office of Management and Budget … on the activities performed by that agency and its Federal laboratories … The report shall include … information on technology transfer activities for the preceding fiscal year [including] (i) the number of patent applications filed; (ii) the number of patents received; (iii) the number of fully-executed licenses which received royalty income in the preceding fiscal year … (iv) the total earned royalty income … [and] (vii) any other parameters or discussion that the agency deems relevant or unique to its practice of technology transfer.

Noted in the TPO's most recent annual report (*Federal Laboratory Technology Transfer Fiscal Year 2016: Summary Report to the President and the Congress*, p. 14), and as a policy

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[6] The Bayh-Dole Act of 1980 brought about the establishment of technology transfer offices at universities.

[7] Federal laboratories, which are, by definition, government owned (GO) can be distinguished by the organization operating the laboratory. Federal laboratories can be government operated (GO) or contractor operated (CO). Thus, federal laboratories are referred to either as GOGO laboratories or GOCO laboratories.

[8] See footnote 4 above.

motivation for the analysis that follows in this paper, is a statement about scientific publications as a technology transfer mechanism:[9,10,11]

> Although intellectual property has traditionally been tracked in terms of the number of patents, licenses, and collaborative efforts [CRADAs], *most federal research results are transferred through publication of S&E [Science and Engineering] articles* (emphasis added).

In the absence of public domain data on scientific publications at the federal laboratory level,[12] we constructed a panel of data on scientific publications from Federally Funded Research and Development Centers (FFRDCs).[13] The panel contains a time series of scientific publications (i.e., journal articles) from FFRDCs websites across the 8 FFRDCs for which such information is made public. Data on the count of scientific publications are available for each of these 8 FFRDCs, by calendar year from 2003 through 2018.

Table 1. Descriptive Information on FFRDCs

FFRDC	**Year formed**	**Agency owner***	**Contractor*****
Argonne National Lab.	1946	DOE	UChicago Argonne, LLC
Brookhaven National Lab.	1947	DOE	Brookhaven Science Associates, LLC
Frederick National Lab. for Cancer Research	1972	HHS	Leidos Biomedical Research, Inc.
Jet Propulsion Lab.	1936	NASA	California Institute of Technology
National Center for Atmospheric Research	1960	NSF	University Corporation for Atmospheric Research
National Renewable Energy Lab.	1974	DOE	Alliance for Sustainable Energy, LLC
Pacific Northwest National Lab.	1965	DOE	Battelle Memorial Institute
SLAC National Accelerator Lab.**	1962	DOE	Stanford University

*Agencies: DOE —Department of Energy, HHS—Health and Human Services/National Institutes of Health, NASA National Aeronautics and Space Administration, NSF —National Science Foundation
**Formally Stanford Linear Accelerator Center (SLAC)
***Contractor information is from https://www.nsf.gov/statistics/ffrdclist/

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[9] Prefacing each fiscal year report from the TPO is the statement: "This report fulfills the requirement of Title 15 of the United States Code, Sect. 3710(g)(2), for an annual report summarizing the use of technology transfer authorities by federal agencies."
[10] Metrics related to scientific publications are conspicuously absent from the TPO's Federal Laboratory Technology Transfer Database v.2015; see, https://www.nist.gov/tpo/reports-and-publications.
[11] The European Commission (EC) takes a broader interpretation of technology transfer metrics than the United States. The EC prefers the term *knowledge transfer metrics*. "[Knowledge transfer] KT is about getting research and expertise put to use which, by its nature, is wide-ranging and complex" (European Commission, p. 7). Regarding the scope of KT indicators, the EC also notes that the primary KT channel is publications and presentations (European Commission, p. 16).
[12] Data on science and engineering (S&E) publications in a selected number of journals by scientists from FFRDCs are available at the aggregate level, not at the agency level or at the laboratory level. See *Science and Engineering Indicators 2018: Appendix Table*; Table 5–41. A distinction is made between peer-reviewed scientific publications, which are considered in this paper, and, for example, contractor reports or conference presentations.
[13] U.S. Federal Acquisition Regulation (FAR 2.101) defines an FFRDC in the following manner: "Federally Funded Research and Development Centers (FFRDCs) means activities that are sponsored under a broad charter by a Government agency (or agencies) for the purpose of performing, analyzing, integrating, supporting, and/or managing basic or applied research and/or development, and that receive 70 percent or more of their financial support from the Government." With reference to footnote 7 above, all FFRDCs are GOCO laboratories.

A description of the 8 FFRDCs that make available online counts of scientific publications is in Table 1, and the primary data on the counts per year are in Table 2.

Table 2. Scientific publication count by calendar year and by FFRDC

	Argonne National Lab.	**Brookhaven National Lab.**	**Frederick National Lab. for Cancer Research**	**Jet Propulsion Lab.**	**National Center for Atmospheric Research (NCAR)**	**National Renewable Energy Lab. (NREL)**	**Pacific Northwest National Lab. (PNNL)**	**SLAC National Accelerator Lab.**
2003	612	607	1	64	458	256	1065	0
2004	393	990	2	94	331	237	1202	1
2005	323	786	2	86	537	258	1765	0
2006	376	807	5	68	575	253	1329	0
2007	740	906	2	77	620	257	1403	2
2008	676	702	3	30	703	292	1481	6
2009	683	770	2	10	586	330	1677	24
2010	737	886	5	21	630	339	2151	48
2011	739	790	3	44	696	359	3234	60
2012	547	712	5	44	758	400	1955	113
2013	278	826	4	67	751	425	1904	107
2014	300	773	5	73	772	496	2059	140
2015	684	655	4	25	792	540	2202	199
2016	990	454	1	109	897	620	1803	182
2017	1045	397	8	54	863	623	1897	152
2018	1607	284	25	50	831	738	1512	179*
Sources								
Argonne	https://www.anl.gov/search-public?btnG=Search#q=(2011)&sort=date%20descending&site=Scientific%20Publications (publication by CY)							
Brookhaven	https://passpubs.bnl.gov/Search (publication by CY date of submission)							
Fredrick	https://frederick.cancer.gov/tsearch/publications?page=1 (sum over 3 labs, publication by CY)							
JPL	https://ntrs.nasa.gov/search.jsp?N=0 (publication by CY)							
NCAR	https://opensky.ucar.edu/islandora/search/%20?islandora_solr_search_navigation=0&sort=keyDate%20asc&f%5B0%5D=collectionName_ms%3A%22Journal%5C%20Articles%22 (publication CY)							
NREL	https://www.nrel.gov/research/publications.html (publication by CY)							
PNNL	https://www.pnnl.gov/publications-reports (publication by CY)							
SLAC	https://portal.slac.stanford.edu/sites/lcls_public/Pages/pub_stats.aspx (publication by CY)							

*This datum is recorded as 17 on the SLAC publication portal. By our count, 179 appears to be the correct number of scientific publications in CY 2018

As discussed in the following section, the relevant variable we will associate with the annual number of scientific publications in FFRDCs is annual public-sector R&D expenditures at FFRDCs. Table 3 shows public-sector R&D expenditures at each of the 8 FFRDCs, by fiscal year from 2003 through 2018.

Table 3. R&D expenditures by fiscal year and by FFRDC (millions, current dollars)

	Argonne National Lab.	**Brookhaven National Lab.**	**Frederick National Lab. for Cancer Research**	**Jet Propulsion Lab.**	**National Center for Atmospheric Research (NCAR)**	**National Renewable Energy Lab. (NREL)**	**Pacific Northwest National Lab. (PNNL)**	**SLAC National Accelerator Lab.**
2003	500.83	452.73	296.00	1390.56	140.76	221.50	679.00	164.75
2004	520.88	450.34	335.00	1551.17	154.71	226.46	692.37	206.40
2005	482.05	483.04	334.40	1606.41	135.89	211.32	779.52	205.69
2006	472.96	490.69	334.50	1548.02	153.34	196.45	749.37	214.03
2007	489.68	510.21	339.80	1717.20	144.29	190.87	851.51	231.96
2008	533.53	480.46	509.70	1733.60	161.13	229.40	885.98	234.32
2009	543.17	569.24	378.20	1711.53	203.63	273.64	1064.23	294.42
2010	650.50	535.55	643.94	1640.34	220.33	326.65	1116.65	354.39
2011	710.44	526.57	431.60	1543.97	198.23	386.54	1095.92	327.72
2012	679.39	516.92	430.10	1493.61	169.74	398.87	1033.77	329.75
2013	708.50	529.63	433.90	1519.26	172.53	347.37	934.49	327.01
2014	719.46	573.36	448.50	1664.54	162.26	360.00	1021.91	316.65
2015	719.52	587.19	495.30	1749.69	166.39	378.44	951.10	310.17
2016	733.38	579.09	642.17	1852.37	177.42	362.09	914.75	313.03
2017	723.82	556.88	704.22	2324.83	171.55	357.92	983.96	327.45
2018	777.25	552.64	748.50	2733.91	158.26	388.50	956.19	341.62

Source: National Science Foundation, National Center for Science and Engineering Statistics, FFRDC Research and Development Survey, multiple years. The primary data in this reference are in thousands of current dollars. The primary data, converted into constant 2012 dollars, are used in the empirical estimations

Analytical analysis and estimates of scientific publication elasticity

Framework for analysis

Previous econometric studies of the output from R&D that have estimated a patent applications elasticity of R&D can be grouped into those using cross-sectional federal agency data (referenced above) and those using cross-sectional private-sector data.[14] Both genres of studies are based on a knowledge production function (Griliches 1979) specification of the form:

$$PatApp = A\ RD^{\alpha} L^{\beta}, \tag{1}$$

where *PatApp* is the count of new patent applications at a point in time or over time; α and β are output elasticities respectively for R&D expenditures, RD, and scientific labor, L, inputs; and A is a constant or disembodied shift factor. For purposes of estimation, Eq. (1), after talking the natural logarithm of both sides of Eq. (1), yields:

$$\log(PatApp) = \log(\mathrm{A}) + \alpha \log(\mathrm{RD}) + \beta \log(L). \tag{2}$$

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[14] See, for example, Hall and Ziedonis (2001) and Czarnitzki, Kraft, and Thorwarth (2009).

With R&D expenditures measured per unit of labor input, Eq. (2) has been estimated through an equivalent Eq. (3):

$$\log(PatApp) = \log(\mathrm{A}) + (\alpha + \beta)\log(L) + \alpha\log(RD/L). \tag{3}$$

The variation of Eq. (1) that we consider in this paper uses scientific publications, *SciPubs*, as the dependent variable. And, a single input publication knowledge production function is used as the basis of our empirical model. Thus:

$$SciPubs = \mathrm{A}\ \mathrm{RD}^{\gamma} \tag{4}$$

where γ is the relevant output elasticity. There is a both a measurement reason as well as a pragmatic reason for our use of a single input publication knowledge production function.

On the measurement side, the single input publication knowledge production function already includes labor input. R&D expenditures, *RD*, include not only a flow into the stock of technical capital that affects innovative output, but also a flow of new labor input that uses the technical capital (and that adds to the human capital that together with the technical capital constitutes the R&D knowledge capital of the FFRDC or research organization more generally). Hence, research employment costs are included in the R&D expenditure measure.[15] Thus, including the input of the variable factor of production labor, L, in a knowledge production function like that in Eq. (1) raises an issue of double counting the contribution of labor to the innovation output.

The double counting issue might not be a trivial one. For example, Link and Scott (2019, 2020) have studied scientific publication activity at NIST. The NIST data show that over the time period 1973 through 2008, labor's relative share of R&D expenditures was between 60 and 70%. More generally, in 2014, the Government Accountability Office (GAO) conducted a study of compensation issues at FFRDCs. They found that across 30 FFRDCs between 2010 and 2012, labor compensation costs as a percent of total funding of the laboratories, which is usually accounted for in terms of their public-sector R&D budgets, ranged from a low of 33% to a high of 79%. While previous cross-sectional studies that were based on a model similar to that in Eq. (1) have thus included the contribution of the labor input twice, the double counting of the labor did provide additional insight, serving to account for differences in scale and, as seen in Eq. (3), serving to account for differences in support per researcher (Adams and Griliches, p. 12668) across the economic units being studied.

On the pragmatic side, measures of labor, L, over time for each of the 8 FFRDCs in the time series panel are not readily available. FFRDCs tend to report online only the current number of employees.

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[15] We thank Michael Gibbons, Research and Development Statistics Program Survey Statistician at the National Science Foundation (NSF), for his electronically shared insight about R&D expenditures allocated to FFRDCs. We also appreciate information learned about data on federally funded R&D at FFRDCs through electronic correspondence with Matt Hourihan, Director of the R&D Budget and Policy Program at the American Association for the Advancement of Science.

Therefore, to estimate the elasticity of scientific publications with respect to public-sector R&D expenditures, the model we estimate is:

$$\log(SciPubs) = \mathrm{A}' + \gamma \log(RD_{-1}) + \boldsymbol{\lambda}\mathbf{X} + \varepsilon, \tag{5}$$

where γ measures the publication elasticity of laboratory R&D lagged one year (RD_{-1}), as discussed below, and $\mathbf{X}$ is a vector including binary variables for each FFRDC to control for fixed effects, and also including analytical time to capture any trend over time.

Our method of analysis ties well to the extant literature. Equation (5) is exactly the model estimated by Adams and Griliches (1996) in their study of the relationship between R&D expenditures and scientific publications at universities, and their description of the model is instructive (p. 12667):

> We estimate several versions of a ''production function,'' of the form $y = \alpha + \beta\ W(r) + \gamma X + \lambda\ t + u$, where y is the logarithm of one of our measures of output (papers or citations), $W(r)$ is the logarithm of a distributed lag function of past R&D expenditures, or the number of S&Es, or both, X is a set of other ''control'' variables such as type of school, and t is a time trend or a set of year or period dummy variables, whereas u represents all other unaccounted forces determining this particular measure of output. Our primary interest centers on the parameters β and λ. The first would measure the returns to the scale of the individual (or rather, university) research effort level, if everything else were correctly specified in this equation, while the second, will indicate the changing general level of ''technology'' used to convert research dollars into papers or citations.

We see from the passage above that in addition to estimating Eq. (5) for scientific publications, Adams and Griliches consider citations of the scientific publications in addition to the count of scientific publications as the measure of output, and they also consider a measure of labor (the number of scientists and engineers, S&Es) as an alternative measure of the inputs.[16] We do not have the measure of labor for the FFRDCs, and we do not have the citations for the papers that FFRDCs produce.[17] However, although Adams and Griliches do make use of the leverage

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[16] Since the measure of labor inputs is used as an alternative to the R&D expenditures, there is no double counting issue that requires interpretation in their main estimating equations. However, Adams and Griliches (1996), in addition to presenting the model with real R&D and then alternatively with S&Es, report (p. 12668) "for good measure … a third specification that includes both S&Es and real R&D per S&E," as in specification (3) above in our discussion of the literature studying patent applications. Adams and Griliches (1996, p. 12668) in their study of university publications observe, "When we add R&D per S&E as a separate variable the main effect of S&Es is about the same but there is an additional effect, generally somewhat smaller yet still significant, of per capita R&D. These findings suggest that not all research is financed by grants, but that departments with more generous support per researcher are more productive. More of the research in the smaller programs is being supported by teaching funds, because the S&E input measure is larger in these programs relative to real R&D." Observe from Eq. (3) that we would expect the per capita R&D effect to be smaller than the estimated effect for the scientific labor term because the effect estimated for the R&D per capita is in fact the output elasticity for R&D expenditures, while the estimated coefficient for the S&E input is the sum of the output elasticity of R&D expenditures and the output elasticity for S&E input.

[17] An extension of an analysis of scientific publication counts, which we discuss in "Concluding remarks" section below, is to relax the assumption that scientific publications are homogeneous in terms of their knowledge content.

afforded by comparing the elasticities for the two measures, their findings are qualitatively similar (although, with a couple of exceptions, somewhat higher for S&Es than for real R&D) for the variations of the dependent and explanatory variables, and that increases confidence in results in our estimations using the scientific publications and real, i.e., constant dollar, R&D expenditures.

Complementing the micro-based research of Adams and Griliches is the macro-based research of Shelton (2008) who relates scientific papers, as a measure of science output, to various measures of R&D investment across countries and through time. We echo the importance of both of these papers through our emphasis on scientific publications as an innovative output associated with R&D.

Empirical findings

Scientific publications from the 8 FFRDCs for which a time series of annual data are publicly available (see Table 2) are (measured with their natural logarithms) the dependent variable in Eq. (5), and the related public-sector R&D expenditures (see Table 3) lagged one year (RD_{-1}) are the independent variable.[18] The one-year lag in the R&D variable is to allow for time between the preparation and submission of research papers and their scientific publication.[19]

The R&D expenditures in Table 3 are in current dollars. For estimation purposes, current dollar R&D expenditures were converted to constant dollar R&D ($2012) using the Gross Domestic Product implicit price deflator.[20,21] Both scientific publications and R&D expenditures enter Eq. (5) as natural logarithms by construction of the model.

Least-squares estimates of Eq. (5) using the panel of data for the 8 FFRDCs observed over the years 2003 through 2018 are presented in column (1) of Table 4. The estimates in column (2) of the table add the variable *trend* (analytical time defined as the year minus 2002) to control for a time trend.

We also examined the questions of whether the 8 FFRDCs have significantly different slope coefficients and whether there are year effects in the data. Neither the different slope effects nor the year effects are statistically significant. For the year effects, we added to specification (1) a complete set of time dummies. With the lagged explanatory variable, we lose the observation for 2003, and then with the year effect for 2004 left in the intercept, we have time dummies for 2005

Adjustments for the heterogeneity of scientific publications, possibly through citation analyses, should be considered in future research. Of course, that would require that federal laboratories not only make available their publication counts, but also their listing of the scientific publications. From our experience, U.S. federal laboratories, as we discussed in footnote 4 above, are even reluctant to provide details of scientific publication counts.

[18] RD is converted first to constant dollars, then to natural logarithms, and then the lagged value enters the equation.

[19] Consider the year 2005. Scientific publications are observed by calendar year and would be in the period January 1 to December 31 of 2005. R&D expenditures are for fiscal years, so the R&D for 2005 would be for the period October 1 of 2004 through September 30 of 2005. R&D is already lagged a bit, and then the additional one-year lag is applied in the estimation of the model.

[20] See https://fred.stlouisfed.org/series/A191RD3A086NBEA (2012 = 100).

[21] See Jankowski (1993) for the use of the implicit price deflator for converting current dollar R&D to constant dollar R&D.

through 2018 for specification (1) without trend. To test for whether the slope coefficients differ across the agencies, we entered the seven interaction terms, for the seven FFRDCs not left in the intercept, with each interaction being the product of the lagged logarithm of constant dollar R&D and the dummy variable for one of the FFRDCs. The extra variables are not statistically significant: For the seven interaction terms, *F*(7, 88) = 1.35, and the probability of a greater *F*-statistic is 0.235. For the 14 year effects, *F*(14, 88) = 0.92, and the probability of a greater *F*-statistic is 0.546.[22]

Table 4. Least-squares estimates from Eq. (5), dependent variable log (*SciPubs*), explanatory variable log (RD_{-1}) with *RD* in constant 2012 dollars (robust standard errors in parentheses)

Variable	**(1)**	**(2)**
log (RD_{-1})	2.1482***	1.5503***
	(0.6722)	(0.5890)
Trend	–	0.0472***
		(0.0150)
Argonne National Lab.	0.9793**	1.4846***
	(0.4632)	(0.4193)
Brookhaven National Lab.	1.4269***	1.8440***
	(0.4018)	(0.3909)
Frederick National Lab. for Cancer Research	− 3.4138***	− 3.1044***
	(0.3568)	(0.3469)
Jet Propulsion Lab.	− 3.7078***	− 2.5984***
	(1.0332)	(0.8805)
National Center for Atmospheric Research	3.8502***	3.5882***
	(0.6829)	(0.6210)
National Renewable Energy Lab.	2.1284***	2.1907***
	(0.4146)	(0.3889)
Pacific Northwest National Lab.	1.1987*	1.9468***
	(0.6557)	(0.5758)
Intercept	− 13.3734**	− 9.0738*
	(5.6069)	(4.9417)
R-squared	0.8984	0.9063
F-statistic	207.58***	174.40***
n	118	118

***Significant at .01-level
**Significant at .05-level
*Significant at .10-level
The *F*-statistic degrees of freedom for column (1) is *F*(8, 109) and for column (2) is *F*(9, 108)
Fixed effect for the SLAC National Accelerator Lab. is included in the intercept term
As shown in Table 3, scientific publications in calendar years 2003, 2005, and 2006 are 0 for the SLAC National Accelerator Lab. Those observations are deleted in the models reported in the table. Separately, scientific publications for those years were set to 0.001, and a binary variable was included as an independent variable equal to 1 for those three years. The estimated scientific publication elasticity of R&D is unchanged

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[22] Adding *trend* to the specification, we have to drop an additional time dummy, because otherwise a linear combination of the column of ones for the intercept and the time dummies equals *trend*; and thus, in the fully specified models with the year effects, the two specifications (1) and (2) with all of the year effects are identical—the 14 year dummies in specification (1) or *trend* and 13 year dummies in specification (2) span the same space, and the tests of joint significance are identical.

Discussion

Based on the coefficient estimates in column (1) of Table 4, on average across the 8 FFRDCs and the years 2003 through 2018, the estimated scientific publications output elasticity of public-sector R&D is 2.15. A 10% increase in constant dollar public-sector R&D is associated with a 21.5% increase in scientific publications. From column (2), where *trend* is held constant, the estimated elasticity is 1.55.

These elasticities are one measure of the return to public-sector expenditures for a sample of federal laboratories. That said, at least two questions remain. The first question is, as related to *The President's Management Agenda*: How important are scientific publications "[f]or America to maintain its position as the leader in global innovation, bring products to market more quickly, grow the economy, and maintain a strong national security innovation base"? The second question is: How representative is the sample of 8 FFRDCs compared to all 43 FFRDCs?

We address the second question first. In fiscal year 2018, the total current dollar public-sector R&D expenditures in all 43 FFRDCs was $21,171.5 million.[23] The total current dollar public-sector R&D expenditures in the 8 FFRDCs studied in this paper was $6656.9 million. Thus, the year 2018 R&D coverage ratio for our sample of 8 FFRDCs is 31.4%.

Regarding the first question, which relates to the social benefits that flow from FFRDC scientific publications, our answer is: "We do not know." What we do know is that several federal agencies, such as the DOC[24] and the DOE,[25] have conducted evaluation studies of specific public-sector R&D-based projects and have concluded that the social rate of return from scientific publications is in double digit percentages. As well, Mansfield (1998, p. 775) studied the impact of published academic research on new industrial products and processes over various time periods and various industries, and he concluded that:

> … over 10% of the new products and processes introduced in [7 major] industries could not have been developed (without substantial delay) in the absence of recent academic research.

A rate of return on R&D knowledge capital

Framework for analysis

In this section, we employ an alternative approach to quantify the impact of public-sector R&D expenditures associated with scientific publications. In particular, we model scientific publications, noted here as Q for specification simplicity in the model that follows, as a function of the R&D-based stock of an FFRDC's scientific knowledge. We again consider the FFRDC's R&D expenditures in each year, but we explicitly model the scientific publications as a function

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[23] See National Science Foundation, National Center for Science and Engineering Statistics, FFRDC Research and Development Survey.

[24] See Link and Scott (2012).

[25] See https://www.energy.gov/eere/analysis/downloads/aggregate-economic-return-investment-us-doe-office-energy-efficiency-and.

of the stock of scientific knowledge, K, with that stock being augmented each year because of R&D expenditures, RD. The publication knowledge production function is thus $Q = A(t)\,f(K)$.

Using the "dot" notation for time derivatives, observe that:

$$\frac{\dot{Q}}{Q} = \frac{\dot{A}}{A} + s_K \frac{\dot{K}}{K}, \tag{6}$$

where s_K is the elasticity of the research output of scientific publications with respect to the stock of scientific knowledge. Thus:

$$s_K = \frac{\partial Q}{\partial K}\frac{K}{Q}. \tag{7}$$

Then, following Terleckyj (1974), we substitute for s_K using (7):

$$\frac{\dot{Q}}{Q} = \frac{\dot{A}}{A} + \frac{\partial Q}{\partial K}\frac{\dot{K}}{Q}. \tag{8}$$

Assuming that for a good approximation we can ignore the depreciation in the scientific knowledge stock, we can use the observed flow of new research expenditures from the preceding period, RD_{-1}, as the value for the relevant increment to the stock of knowledge $\dot{K}$. Thus, our estimable equation is:

$$\frac{\dot{Q}}{Q} = \frac{\dot{A}}{A} + \frac{\partial Q}{\partial K}\frac{RD_{-1}}{Q}. \tag{9}$$

To estimate the rate of return to scientific publications from investments in knowledge capital, $\partial Q/\partial K$, we use the estimated coefficient on RD_{-1}/Q from Eq. (9), and to estimate the rate of technological change in the knowledge production function, $\dot{A}/A$, we use the estimated intercept from Eq. (9).

Empirical findings

Table 5 provides the least-squares estimates for Eq. (9) using the panel data for the 8 FFRDCs for new scientific publications and constant dollar R&D expenditures for 2003 through 2018. In contrast to the model of the elasticity of scientific publications with respect to R&D expenditures as shown in Table 4, the model of the rate of return of scientific publications from investments in knowledge capital shown in Table 5 finds that the slope effects and also the year effects are often statistically significant, and so we present the results with the full set of intercept and slope effects and the year effects estimated.[26] Thus, for each FFRDC, there are separate estimates for

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[26] The variable *trend* is not included, because with the fully specified model, a specification with *trend* included is identical to the estimated model. If *trend* is added, then in addition to dropping the time dummy for 2018 because we lose those observations from the construction of the dependent variable, and for 2003 because of the variable for

the rate of return, $\partial Q/\partial K$, and for the rate of technological change in the knowledge production function, $\dot{A}/A$.

Table 5. Least-squares estimates from Eq. (9), dependent variable $\dot{Q}/Q$

Variable	**(1) Coefficient (robust standard error)**	**(2) Coefficient (standard error clustered by lab)**
RD$_{-1}$/Q	0.000181	0.000181
	(0.000691)	(0.000142)
Slope effect: coefficient on the product of RD$_{-1}$/Q and qualitative variable = 1 for the laboratory indicated, and 0 otherwise		
Argonne National Lab.	0.0400	0.0400***
	(0.0254)	(0.00803)
Brookhaven National Lab.	− 0.0945*	− 0.0945
	(0.0559)	(0.0672)
Frederick National Lab. for Cancer Research	0.00142*	0.00142***
	(0.000763)	(0.000151)
Jet Propulsion Lab.	0.000916	0.000916***
	(0.000814)	(0.000113)
National Center for Atmospheric Research	0.408***	0.408**
	(0.123)	(0.128)
National Renewable Energy Lab.	0.105	0.105
	(0.0671)	(0.0587)
Pacific Northwest National Lab.	0.279*	0.279***
	(0.154)	(0.0662)
Intercept effect: coefficient on qualitative variable = 1 for the laboratory indicated, and 0 otherwise		
Argonne National Lab.	− 0.806*	− 0.806***
	(0.430)	(0.0965)
Brookhaven National Lab.	0.166)	0.166
	(0.536)	(0.563)
Frederick National Lab. for Cancer Research	− 2.30***	− 2.30***
	(0.677)	(0.0903)
Jet Propulsion Lab.	− 0.753*	− 0.753***
	(0.411)	(0.0542)
National Center for Atmospheric Research	− 1.54***	− 1.54***
	(0.482)	(0.311)
National Renewable Energy Lab.	− 1.29*	− 1.29**
	(0.651)	(0.446)
Pacific Northwest National Lab.	− 1.93**	− 1.93***
	(0.816)	(0.315)
Intercept[a]	− 0.0718	− 0.0718
	(0.375)	(0.362)
Year effects[b]	Yes	Yes
R-squared	0.595	0.595
Model statistic[c]	*F*(28, 81) = 2.51***	
n[d]	110	110

***Significant at .01-level
**Significant at .05-level

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lagged R&D over quantity, and for 2004 because it is left in the intercept, another of the year dummy variables must be dropped because otherwise a linear combination of the time dummies and the intercept would equal the variable *trend*. The two models, one without *trend* and the year dummy variables for 2005 through 2017, and the other with *trend* and the year dummy variables for 2006 through 2017, are equivalent because the sets of time effects span the same space.

*Significant at .10-level

[a]Fixed effect for the SLAC National Accelerator Lab. is included in the intercept term

[b]Because of the construction of the dependent variable, we are missing 2018 for that variable. Because of the lagged R&D to output variable, we are missing 2003 for that variable. Thus, leaving 2004 in the intercept, we enter time qualitative variables for 2005 through 2017

[c]The parameters estimated are for the most part statistically significant using clustered standard errors. With the clustering at the laboratory level and with only the eight clusters, the small sample model *F*-statistic cannot be computed because the number of clusters places an upper bound on the number of independently distributed constraints for which joint significance can be tested. Within each cluster, it is assumed that the errors are not independently distributed, and the number of clusters is less than the number of parameters estimated, the joint significance of which would be assessed with the model statistic. The joint significance of subsets of parameters, fewer in number than the clusters, can be tested. Thus, the individual parameter tests with the clustered standard errors are valid because they each entail a single constraint. Similarly, the *F*-statistics, computed with the clustered standard errors and presented in Table 6, for the significance of estimates for each individual laboratory's intercept and slope are valid, as are the *F*-statistics for the averages of those estimates that are discussed in the text

[d]As shown in Table 3, scientific publications in calendar years 2003, 2005, and 2006 are 0 for the SLAC National Accelerator Lab. For the observations where one of those values would cause the dependent or explanatory variable to be undefined, the observations were not used

Discussion

The estimated coefficient for the flow per unit of output of new lagged research expenditures is the estimate for the SLAC National Accelerator Lab. for $\partial Q/\partial K$, the annual rate of return to the stock of scientific knowledge. (See note a to Table 5.) Then to have the estimate of $\partial Q/\partial K$ for each of the other FFRDCs the coefficient on the interaction term for the laboratory is added to the estimate for the SLAC National Accelerator Lab. The estimated value of $\partial Q/\partial K$ for each laboratory is shown in Table 6. Table 5 provides the statistical significance of the difference in each laboratory's estimate from the estimate for the SLAC Lab., and Table 6 provides the *F*-statistic and statistical significance of each laboratory's estimated $\partial Q/\partial K$.

Using the estimates in Table 6, the annual rate of return to the knowledge stock is estimated on average across the 8 FFRDCs to be 0.0927 or 927 scientific publications from the addition of \$10 million in knowledge stock (or 93 scientific publications for an additional \$1 million in knowledge stock), and that estimate is statistically significant.[27,28,29] The calculated average hides a large amount of variability across the FFRDCs. Among the statistically significant estimates, there is a large range from 1.1 and 1.6 publications per additional million dollars of knowledge stock for Jet Propulsion Lab. and Frederick National Lab. respectively to 408 publications per additional million dollars of knowledge stock for National Center for Atmospheric Research, with Argonne National Lab. and Pacific Northwest National Lab.

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[27] Using the robust standard errors, the F-statistic for the average equal to zero is $F(1, 81) = 9.44$, with the probability of a greater $F = 0.0029$. Using the clustered standard errors, the *F*-statistic is $F(1, 7) = 17.61$, with the p value = 0.0041.

[28] The finding about the rate of return here is two orders of magnitude larger than the rate of return (7.3 scientific publications for an additional \$10 million in knowledge stock) reported in Link and Scott (2019) for the federal laboratory NIST during the NIST era (i.e., since the National Bureau of Standards was reorganized and renamed as the National Institute of Standards and Technology). Perhaps the difference is related to the many channels through which NIST transfers knowledge, or possibly to the different operating structures of the labs. See footnote 7 above. The FFRDCs are GOCO laboratories, while NIST is a GOGO laboratory.

[29] The primary data on R&D are in thousands of dollars. See the note to Table 3.

respectively, at 40 and 279 scientific publications per additional million dollars of knowledge stock occupying a very wide middle ground.

Table 6. Estimates of $\partial Q/\partial K$ and $\dot{A}/A$ for each FFRDC

Laboratory	**$\partial Q/\partial K$ [F(1, 81)], robust**[a]	**$\partial Q/\partial K$ [F(1, 7)], clustered**[b]	**$\dot{A}/A$ [F(1, 81)] robust**[c]	**$\dot{A}/A$ [F(1, 7)] clustered**[d]
Argonne National Lab.	0.0402	0.0402***	− 0.313	− 0.313**
	[2.50]	[24.8]	[1.42]	[9.75]
Brookhaven National Lab.	− 0.0943*	− 0.0943	0.659	0.659
	[2.86]	[1.98]	[2.26]	[1.61]
Frederick National Lab. for Cancer Research	0.00160***	0.00160***	− 1.80***	− 1.80***
	[25.2]	[1315.3]	[9.50]	[636.45]
Jet Propulsion Lab.	0.00110**	0.00110***	− 0.259	− 0.259**
	[5.90]	[42.1]	[0.96]	[10.95]
National Center for Atmospheric Research	0.408***	0.408**	− 1.04***	− 1.04**
	[11.0]	[10.1]	[9.30]	[8.76]
National Renewable Energy Lab.	0.106	0.106	− 0.785	− 0.785
	[2.48]	[3.23]	[2.08]	[2.62]
Pacific Northwest National Lab.	0.279*	0.279***	− 1.43*	− 1.43***
	[3.29]	[17.7]	[3.23]	[16.63]
SLAC National Accelerator Lab.	0.000181	0.000181	0.493	0.493***
	[0.07]	[1.63]	[2.56]	[109.30]

***Significant at .01-level

**Significant at .05-level

*Significant at .10-level

[a] The *F*-statistic uses the non-clustered robust standard errors. Excepting the case (SLAC) left in the intercept, the test is for whether the sum of two estimated coefficients equals zero.

[b] The *F*-statistic uses the clustered standard errors. Excepting the case (SLAC) left in the intercept, the test is for whether the sum of two estimated coefficients equals zero

[c] The *F*-statistic uses the non-clustered robust standard errors. The test is for whether the estimate equals zero. For the laboratories not left in the intercept, for each laboratory the estimate is the average of the 14 years of estimates of the rate of growth in the shift factor *A*, with the first-year, 2004, estimate being the constant term plus the coefficient on the laboratory's dummy variable, and then the subsequent-year estimates (for years 2005 through 2017) being the first-year estimate plus the coefficient on the year effect for the appropriate year. For the laboratory left in the intercept, the estimate is the average of the 14 years of estimates, with the first-year estimate being the constant term, and then the subsequent-year estimates being the constant term plus the coefficient on the year effect for the appropriate year

[d] The *F*-statistic uses the clustered standard errors, and the test is the one described in note *c*

Care must be exhibited when generalizing from the finding, on average across the FFRDCs, of 93 scientific publications per an additional $1 million in knowledge stock, or from the statistically significant estimates for individual laboratories. This metric should be viewed as an index to illustrate what is, meaning it is an index to provide a benchmark for the return to scientific publications in our specific sample panel of 8 FFRDCs. As more studies emerge, and as similar indices are calculated, then suggestive inferences about scientific publication efficiency might be possible. However, this index for the rate of return on the knowledge stock is related to the return to R&D expenditure elasticity measure in the following "Concluding remarks" section.

The intercept estimated in Table 5 shows for the base year of 2004 for the SLAC National Accelerator Lab. the annual growth rate in the shift factor $\dot{A}/A$ for the production function, and the estimated intercepts in the base year for each of the remaining FFRDCs are found by adding their estimated intercept effects to the estimated effect for the SLAC Lab. The estimated value of $\dot{A}/A$ for a laboratory in any subsequent year is found by adding the estimated year-effect for that year. Table 6 provides for each of the laboratories the estimate of its average (over the 14 years from 2004 through 2017 for which we have the estimates) annual growth rate in the shift factor $\dot{A}/A$.[30] Table 6 provides the F-statistic and the statistical significance for each laboratory's average estimated value of $\dot{A}/A$. On average for the 8 FFRDCs, the estimated value is –0.683; thus, on average, across the 8 laboratories and across the years, the production function exhibits a strong negative shift at the rate of 68% per year over the years in the sample.[31]

Comparing the estimates in Tables 4 and 5, we see that, holding constant R&D expenditures, there are statistically significant differences in the levels of scientific publications across FFRDCs, in the scientific publication rates of return to investments, and in the rates of change over time in scientific publications once R&D expenditures relative to output are controlled.

Thus, to summarize, the statistically significant result from Table 5, about the absolute change in scientific publications in response to increases in the knowledge stock, complements the findings about the elasticity of scientific publications in response to greater research expenditures in Table 4. Further, for the particular set of FFRDCs in the sample, the rate of technological change, as measured by production function's shift factor's rate of change, has for all but two (and the estimate for one of those is insignificant) of the laboratories been negative over the period of our sample.

Concluding remarks

This paper contributes to the related literature not only by providing initial information relevant to a return to R&D metric using federal laboratory data but also by emphasizing that scientific publications are an important, and overlooked, innovation output or knowledge-based technology transfer mechanism from research in federal laboratories.

As with many studies that focus on a variable relatively new to the literature, areas for greater investigation are frequently discovered. And, viewing this paper as such a study, care should be made when generalizing from our findings to either all FFRDCs or all federal laboratories. Yet, we point out through an example that the quantitative findings from the alternative models estimated are complementary and thus robust. Although complementary and robust, our estimates might underestimate the return to R&D. As Stam and van de Ven (2019) emphasize, elements of an ecosystem are complementary, thus the channels relevant to more broadly defined

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[30] The finding about the rate of technological change can be compared with the finding in Link and Scott (2020) for the federal laboratory NIST for which a strong negative rate of change in the shift factor was found. While a difference might have been anticipated because of the different operating structures, in fact the results for most laboratories are similar, with one of the two exceptions being statistically insignificant. See footnote 7 above; the FFRDCs in our sample are all GOCO laboratories, while NIST is a GOGO laboratory.

[31] The average is statistically significant. Using the robust standard errors, $F(1, 81) = 15.44$, with p value = 0.0002. Using the clustered standard errors, $F(1, 7) = 34.38$, with p value = 0.0006.

knowledge transfers and the associated indicators are likely to be complementary, and that possibility has not been taken into account in this paper because of data constraints.

Our first quantitative finding is an elasticity of scientific publications with respect to R&D expenditures; the second quantitative finding is an annual rate of return (in terms of scientific publications) on the stock of knowledge. The two findings are complementary. Consider the following hypothetical, yet realistic from an inspection of the data for the FFRDCs, example. From the estimated elasticity of about 1.5, if scientific publications per year for the hypothetical laboratory were 400, if R&D expenditure each year were $500 million, and if there was an increase in R&D expenditure in every year to $550 million, 460 scientific publications per year would result (400 × 1.15). The hypothetical laboratory that had 400 scientific publications a year before the increase in R&D spending has a knowledge stock with some unobserved value. Suppose the hypothetical laboratory is one where, similar to what we have estimated for the Jet Propulsion Lab., the second quantitative finding says that at the margin, whatever that unobserved knowledge stock value is, the increase per year in scientific publications for an additional $10 million in that unobserved value would be 12 scientific publications. From the first finding we see that an additional $50 million in R&D spending each year generates 60 more scientific publications each year. From the second quantitative finding of the estimated rate of return on the investment in the knowledge stock, an additional $10 million in knowledge stock is associated with 12 scientific publications a year, so $50 million in additional value of the knowledge stock would be associated with (12 × 5) or 60 scientific publications. Thus, for the hypothetical example, suppose that the $500 million in annual R&D expenditure maintains a knowledge stock of $5 billion. Increasing its annual R&D spending from $500 million to $550 million, and ignoring any additional annual depreciation in the knowledge stock, the agency increases the value of its knowledge stock by $50 million dollars, and it would then expect to have 460 scientific publications per year rather than 400.[32]

Regarding future research on the return to public-sector R&D expenditures in federal laboratories, one obvious area for future study is to expand the sampling population from FFRDCs to all federal laboratories. However, as we have already mentioned, experience suggests (Link and Oliver 2020) that this is easier said than done. We learned from this study that scientific publications, while viewed by the TPO as a, if not the, key technology transfer mechanism, are not usually found on the webpages of FFRDCs' offices of technology transfer or elsewhere. If the scientific publications were tracked and reported on the webpages, studies of the citation weighted scientific publications, or simply the numbers of citations as in the Adams and Griliches (1996) study of the scientific publications from university research, might be a first step toward understanding a dimension of the social benefits associated with scientific publication from federal laboratories.[33]

Another area for future study is to explore, possibly through detailed case studies, the relationship between scientific publications as a technology transfer mechanism and other, more widely viewed technology transfer mechanisms or technology transfer channels. For example,

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[32] The elasticity of the research output of scientific publications with respect to the stock of scientific knowledge (specified in Eq. (7)) approaches the elasticity of output with respect to R&D expenditure as the annual depreciation rate of knowledge stock approaches 100%.

[33] Again, see footnote 4 above.

consider the following potential research questions. Do scientific publications generally follow from new invention disclosures in federal laboratories, or does the relationship go in the other direction? Are scientific publications a signaling device by federal laboratories for the development of CRADAs with private sector firms or other organizations?[34] Also, building on the conceptualization by Stam and van de Ven (2019) and the insight offered in the European Commission report (European Commission 2020), explicit consideration should be given to other channels through which R&D-based knowledge enters society. The European Commission (p. 16) noted several channels (e.g., networking, consultancy, collaborative research, licensing, and spinoffs) which future research should consider, although at the top of the Commission's list is publication and presentations. Along these lines, an element of future research might include the development of indices that measure a laboratory's use of complementary knowledge transfer channels. Such indices would be similar to existing measures of a laboratory's technology transfer office's efficiency in, for example, converting invention disclosures to patent applications or patents issued to patent licensing revenues.[35]

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[34] Much of the literature on CRADAs is reviewed in Chen et al. (2018).

[35] See Choudhry and Ponzio (2020).

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