An economic analysis of standard reference materials

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Abstract:

Standard Reference Materials® (SRMs®) are high-technology infrastructural elements developed and distributed by the U.S. national metrology institute, the National Institute of Standards and Technology. SRMs are used throughout the economy to enhance production efficiency by reducing information asymmetries and thereby reducing transaction costs between affected parties. To date, the domestic market demand for SRMs in the United States has not been studied. Thus, the purpose of this paper is to estimate a market demand model for SRMs; the empirical results show that market demand is cyclical, that is it increases with positive changes in multifactor productivity.

Keywords: standard reference materials | NIST | R&D | multifactor productivity

Article:

1 Introduction

> Right is right even if no one is doing it; wrong is wrong even if everyone is doing it.
>
> Saint Augustine

Standard Reference Materials (SRMs)Footnote1:

> … are used to perform instrument calibrations in units as part of overall quality assurance programs, to verify the accuracy of specific measurements and to support the development of new measurement methods … An SRM is prepared and used for three main purposes: (1) to help develop accurate methods of analysis; (2) to calibrate measurement systems used to facilitate exchange of goods, institute quality control, determine performance characteristics, or measure a property at the state-of-the-art limit; and (3) to ensure the long-term adequacy and integrity of measurement quality assurance programs.

As background, the National Bureau of Standards (NBS), which became the National Institute of Standards and Technology (NIST) in 1988 through the Omnibus Trade and Competitiveness Act of 1988 (Public Law 100–418),Footnote2 had a pioneering role in the United States in the establishment of SRMs for more than a century.Footnote3 As chronicled by Schooley (2000, p. 110), the Standard Reference Materials program at NBS traces its origin to its response to the American Foundrymen's Association request in 1905 "for help in producing standard samples of cast iron to promote uniform analytical and manufacturing techniques." But it was not until 1964 that a formal Office of Standard Reference Materials was established "to evaluate the requirements of science and industry for carefully characterized reference materials and to stimulate NBS efforts to create, produce, and distribute such materials."Footnote4 Today, the Office of Reference Materials (ORM) at NIST "operates and maintains the business information systems to support customer, financial, inventory, project tracking, and sales functions related to both the SRM program and calibration services."Footnote5 More than 1,300 SRMs are currently certified and maintained at NIST. However, an analysis of industry's demand for SRMs to maintain quality assurance in production and manufacturing has yet to be considered from an economic perspective in either the academic or professional literatures.

The remainder of this paper is organized as follows. In Sect. 2, we offer examples of SRMs developed and maintained at NIST in an effort to provide context for this study. Our examples illustrate the breadth of the economic impacts of SRMs on the economy. Our examples also illustrate that SRMs are a process input, and as such their embodied technology is transferred directly from NIST to SRM consumers and then indirectly to society.Footnote6 As Tassey (2017, p. 29) pointed out about standards in general:

> [T]oday's high-tech economy requires a pervasive highly technical infrastructure to achieve economic efficiency. Developing the new highly complex technologies of the modern economy requires sophisticated research and development methods. These methods are based on a wide range of techniques, or "infratechnologies," such as critically evaluated science and engineering data on new materials' properties, measurement and test methods, and performance metrics. The majority of these infratechnologies become standards to improve the efficiency of R&D and the transfer [emphasis added] of its results.

In Sect. 3, we illustrate, by year, the U.S. market's demand for SRMs, and we identify statistically significant covariates to explain year-by-year variation in that demand.

Finally, in Sect. 4, we summarize our results; we offer a possible roadmap for future study of the public sector's funding support of SRMs, in particular, and of metrology (i.e., measurement science), in general; and we suggest the policy relevance of our findings.

2 Examples of NIST SRMs

The three examples that follow illustrate the technology transfer nature of SRMs, and thus the impact of these SRMs on society.Footnote7

2.1 Cholesterol SRMsFootnote8

Cholesterol is a waxy substance found in the blood stream and in cells. Produced in the liver, cholesterol is a key building block for body tissue. However, if an individual has too much LDL (low-density lipoprotein) cholesterol, blood vessels can become blocked, which can lead to heart disease (Leech & Belmont, 2000). LDL is often referred to by the term bad cholesterol.

NIST currently offers three SRMs related to cholesterol. SRM 911c is pure cholesterol and a 2 g package currently (meaning fiscal year 2021 here and in the examples below) sells for $870, SRM 909 is characterized for cholesterol and other compounds of clinical interest in frozen human serum, and three 2 mL vials currently sell for $943, and SRM 1951 is characterized for cholesterol and glycerides in frozen human serum, and four 1 mL vials currently sell for $834. These SRMs are used by manufacturers of cholesterol measurement calibrators and by research clinicians. The economic benefits associated with use of these SRMs is improved accuracy in patient testing and in reduced variability among laboratories. Reduced variability and improved accuracy in testing lower the transaction costs between producers of test equipment and consumers of test equipment results.

2.2 RadiopharmaceuticalsFootnote9

Radiopharmaceuticals are radioactive drugs that target specific organs or tissues in the human body. They are used for diagnostics (e.g., imaging) as well as for therapeutic purposes. Currently, NIST produces nine radiopharmaceuticals intended for the calibration of radioactivity-measuring instruments. Each SRM is contained in a 5 mL flame-sealed glass ampoule. Because of the short half-life of the radioactive substances, these SRMs are only produced at NIST at certain times of the year; radiopharmaceuticals available from NIST in 2021 are described in Table 1.Footnote10 The economic benefits associated with the use of these SRMs relate to both diagnostic and laboratory research accuracy as well as therapeutics. For example, thallium-201 is used for diagnosis of cardiac disorders, and iodine-125 is used in the treatment of prostate cancer. More accurate diagnoses and laboratory research results in reduced costs, and more accurate and precise treatments are more effective.

Table 1. Radiopharmaceutical SRMs available from NIST

SRM	Description	Month available
4401L	Iodine-131 Radioactivity Standard	February
4404L	Thallium-201 Radioactivity Standard	June
4407L	Iodine-125 Radioactivity Standard	December
4410H	Technetium-99 m Radioactivity Standard	September
4412L	Molybdenum-99 Radioactivity Standard	April
4415L	Xenon-133 Radioactivity Standard	September
4416L	Gallium-67 Radioactivity Standard	May
4417L	Indium-111 Radioactivity Standard	August
4427L	Yttrium-90 Radioactivity Standard	October

Source: https://www.nist.gov/system/files/documents/2021/02/16/2021SRMCatalog_WEB.pdf

2.3 Sulfur measurementFootnote11

Sulfur dioxide (SO2) results from the combustion of fuels in which sulfur is an impurity, and there are two reasons for measuring SO2 accurately. SO2 is harmful not only to the respiratory system of individuals,Footnote12 but also to the efficiency of products that use fossil fuels (e.g., catalytic converters). Production processes are less efficient when sulfur is present (e.g., the quality of steel is compromised when the sulfur content of coke is too high). NIST developed and NIST distributed SRMs allow for accuracy in the measurement of sulfur, and they reduce measurement bias; they not only reduce transaction costs between producers and consumers of fossil fuels but also their use increases production efficiency.

There are many other SRMs available from NIST that are related to sulfur in fossil fuels, and in both ferrous and nonferrous metals.Footnote13

3 Empirical analysis

3.1 The data and hypotheses

As stated above, the purpose of this paper is to identify statistically covariates to explain year-by-year variation in the domestic market demand for SRMs. To date, information about market demand for SRMs (or for other measurement metrics) has been lacking because of hindered access to historical SRM data (Link, 2021a).

Information on the number of SRMs sold in the United States by NIST over the fiscal years 1988 through 2019 (the latest fiscal year for which the data are available) was graciously supplied by the ORM at NIST. See Table 2; these data represent the extent of available information on SRMs produced at NIST. Figure 1 illustrates that over the past three decades, the trend in the domestic market demand for SRMs has been declining, and the decline was greatest during the 1990s compared to the decades following.Footnote14

Information on which SRMs were sold in each fiscal year and to whom they were sold is not publicly available.

Economics has long acknowledged the informational benefits associated with measurement standards. This thread of awareness traces not only to Adam Smith's (1914, originally 1776) discussion of how such standards influence the effectiveness of trade and economic growth, but also to Alfred Marshall's (1920) explanation of how measurement standards increase industrial production.Footnote15

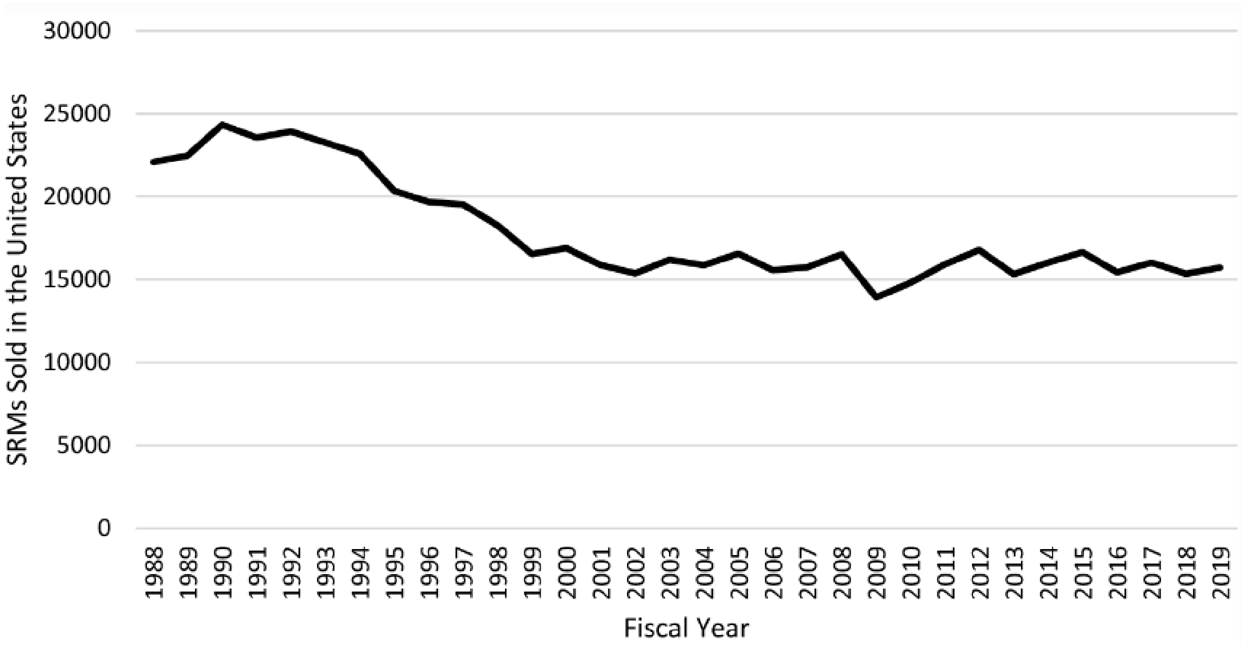
In general, the use of measurement standards by producers enhances production efficiency. A common source of market failure is asymmetry of information; SRMs reduce information asymmetry and thus they reduce transaction costs between affected parties (Link, 2021a, b). As explained by Robertson and Swanepoel (2015, pp. 8–9):

> Asymmetric information between buyers and sellers is one of the most common sources of market failure, which occurs when the buyer cannot determine the quality of a product and as a result does not purchase the product … Transaction costs arise as a result of the information between consumers and producers being asymmetric and incomplete. By having an agreed standard of measurement, a buyer can spend less time searching for goods and incur fewer costs associated with checking that the product conforms to the quality requirements … By producing a product in accordance with the standard, a producer can incur fewer costs associated with correcting defects to meet specifications, which allows for the product to be certified and also leads to trust regarding the certification and performance of the product compared to a competitor's product.

Table 2. SRMs Units Sold, by Fiscal Years 1988–2019

Fiscal year	Total SRM units sold	SRM units sold to customers in the United States
1988	44,484	*22,078*
1989	45,286	*22,476*
1990	49,060	*24,349*
1991	47,491	*23,571*
1992	48,227	*23,936*
1993	46,845	*23,250*
1994	45,488	*22,577*
1995	41,034	*20,366*
1996	39,643	*19,676*
1997	39,358	*19,534*
1998	36,814	*18,271*
1999	33,347	*16,551*
2000	34,020	*16,885*
2001	31,985	*15,875*
2002	30,996	*15,384*
2003	29,527	*16,208*
2004	30,490	*15,875*
2005	32,163	*16,575*
2006	31,195	*15,559*
2007	32,614	*15,741*
2008	33,373	*16,522*
2009	29,769	*13,915*
2010	31,667	*14,812*
2011	32,864	*15,907*
2012	33,441	*16,791*
2013	32,267	*15,328*
2014	32,636	*16,023*
2015	33,490	*16,654*
2016	31,938	*15,447*
2017	32,348	*16,032*
2018	31,503	*15,360*
2019	29,955	*15,714*

Total SRM units sold from FY1988 through FY2019 were provided by the Office of Reference Materials (ORM). The ORM also provided SRM units sold to customers in the United States from FY2003 through FY2019. There was a change in records management in 2003; thus, SRM units sold in the United States prior to that fiscal year were estimated by imputing the mean percentage of SRM units sold in the United States from FY2003 through FY2019 (49.63%) to the total SRM units sold from FY1988 through FY2002 (shown in italics)



Number of SRMs Sold in the United States by NIST, by Fiscal Years 1988 – 2019

And similarly, Swann (2009, p. iv) explained:

> The use of measurement can increase the productivity of organisations … The more precise is the measurement and the more rapid is the feedback from measurement to control, the greater are the effects on efficiency, quality and productivity.

These arguments form the basis of the empirical information in the literature, albeit limited, about the economic impact of measurement standards on production efficiency. As Link (2021a) emphasized, the academic literature is limited in terms of statistical studies about the connection between activities related to measurement science and economic activity. For example, Temple and Williams (2002) studied the impact of measurement science on changes in total factor productivity in the United Kingdom; Choudhary et al. (2013) estimated the impact on bilateral trade among European Union countries; and Link (2021b) estimated the impact of calibration tests on multifactor productivity in the U.S. business sector.Footnote16 Most recently, Blind et al. (2022) estimated the positive long-term impact that standards have on economic growth using aggregate data for 11 European Union (EU-15) countries.Footnote17

Along with this literature, there are a number of case studies that estimate a social rate of return to investments in a particular standard.Footnote18 To the best of our knowledge, no study in the literature has focused systematically on the U.S. domestic market demand for SRMs at any level of aggregation.

The model we consider in this paper focuses on the domestic market demand for SRMs in the United States, and it takes the form:

$$SRMs = f\,(Productivity, \mathrm{X}),$$

where SRMs is the fiscal year (FY) count of SRM units purchased in the United States (see Table 2), Productivity is measured by a multifactor productivity index, MFP, and X is a vector of controls including a control for NIST's price of SRMs and its supply of SRMs.Footnote19

We posit two hypotheses about the relationship between MFP and SRMs. On the one hand, the relationship might be positive to the extent that MFP proxies an income effect on the demand for SRMs. On the other hand, the relationship might be negative to the extent that firms invest in SRMs as a countercyclical strategy to increase internal productivity during periods of economic decline.

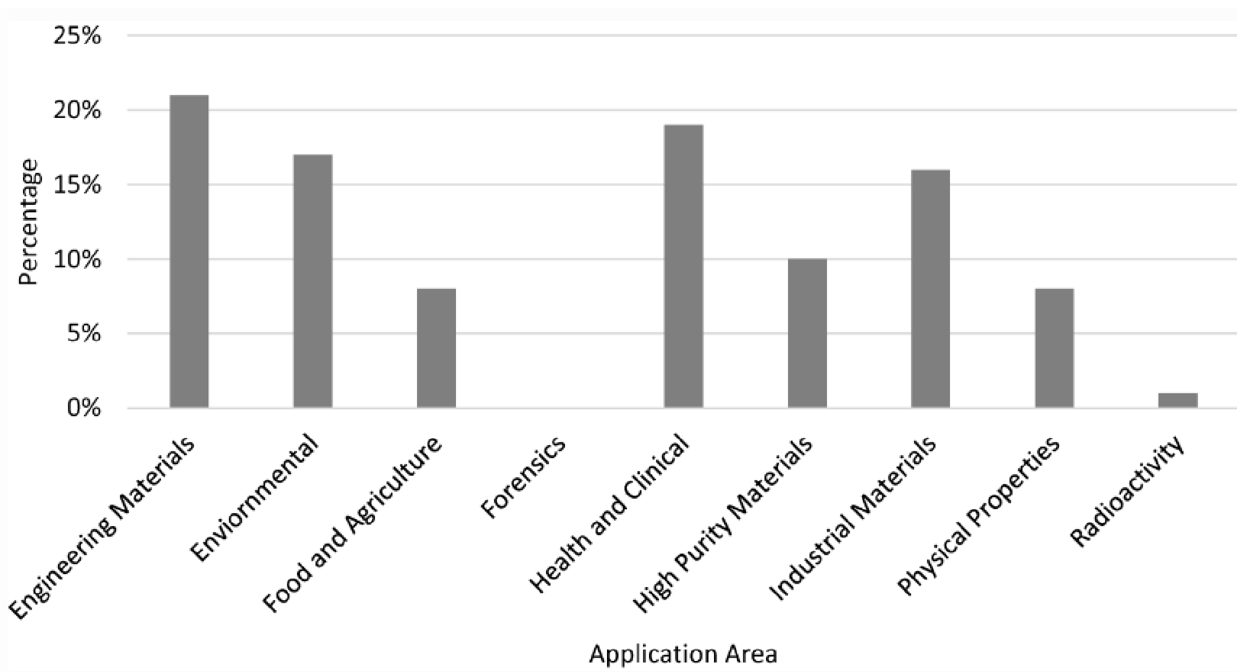
We expect the price of SRMs to be negatively related to the count of SRMs.Footnote20

3.2 Econometric issues

We consider the following demand equation:

$$SRM_{st} = \beta_0 + \beta_1 Price_t + \beta_2 MFP_{t-1} + \beta_3 Supply_{t+\epsilon t}$$

where SRMs is units of SRMs sold by NIST in the domestic market in a fiscal year; Price controls for the price of SRMs; lagged MFP is a private sector multifactor productivity index; and Supply represents the supply of SRMs by NIST in a fiscal year as proxied by the ratio of NIST's laboratory research and development (R&D) budget relative to NIST's total operating budget. Changes in Price represent movement along the domestic market demand and changes in MFP represents shifts in the domestic market demand, the domestic supply of SRMs (Supply) being held constant.



Scope of uses of NIST's SRMs for FY2020

Data on a composite price index for the fiscal year price of a vector of SRMs, Price, are not available either from NIST or elsewhere. However, the ORM at NIST did provide us data on the cost of goods sold per fiscal year. An ordinary least squared (OLS) regression, with serial correlation corrections, of a linear trend against the cost of goods yielded an R2 of 0.88. Thus, our estimation model proxies Price by a trend variable, Trend.Footnote21

An aggregate multifactor productivity index, MFP, is used because use of SRMs is applicable in all sectors of the economy as shown in Fig. 2. MFP enters the regression with a one-year lag for two reasons. First, as mentioned above, the lag structure reduces simultaneity concerns with the outcome variable; and second, because changes in productivity are unlikely to affect private sector SRM demand immediately.

Our measure of Supply is as follows. As the relative share of NIST's total R&D budget is allocated to laboratory research increases, we assume the relative priority for research at NIST increases and thus the greater the ability of a laboratory to justify a new or expanded research agenda. Thus, over time the supply of SRMs (as well as other laboratory outputs) will increase.

Table 3. Definition of the variables

Variable	Definition	Source
SRMs	Fiscal Year domestic SRM units sold in the United States by ORM at NIST	ORM at NIST
Trend	Linear time trend	Constructed by the authors
LabBudget	NIST's laboratory R&D budget	American Association for the Advancement of Science (AAAS), https://www.aaas.org/programs/r-d-budget-and-policy/historical-trends-federal-rd
MFP	Multifactor productivity index for the private business sector (2012 = 100)	Bureau of Labor Statistics, https://www.bls.gov/mfp/tables.htm
Supply	Ratio of NIST's laboratory R&D to NIST's total R&D	American Association for the Advancement of Science (AAAS), https://www.aaas.org/programs/r-d-budget-and-policy/historical-trends-federal-rd

To obtain reliable coefficient estimates from a time series regression estimated by ordinary least squares, all variables must be stationary.Footnote22 Accordingly, we ran Augmented Dickey-Fuller (ADF) tests for SRMs, MFP and Supply. The ADF tests the null hypothesis that a variable follows a unit root process (and is therefore nonstationary) against the alternative that the series is stationary. The test fails to reject the null hypothesis for SRMs and MFP but indicates that Supply is stationary. First differencing SRMs and MFP, and re-running ADF tests, shows the differenced series to be stationary. Our estimated linear regression equation therefore takes the following form:

$$\Delta SRM_{st} = \beta_0 + \beta_1 Trend_t + \beta 2 \Delta MFP_{t-1} + \beta_3 Supply_t + \epsilon_t$$

To ease an interpretation of the Supply coefficient, we standardize the ratio of NIST's laboratory R&D budget to NIST's total operating budget so that a unit change in Supply is equal to one standard deviation.

Our baseline results for this linear model are estimated by ordinary least squares. However, since the level of our outcome variable consists of count data, we also implement a Poisson regression estimated by maximum likelihood estimation (MLE) after adjusting ΔSRMs to positive values.Footnote23

3.3 Descriptive statistics and empirical findings

Descriptive statistics for the levels of the variables used in our regression analysis are presented in Table 4. Over the FY1990 – FY2019 sample period,Footnote24 the average number of SRM units sold ($SRMs$) in a given year was 17,623. The maximum number of units sold was 24,349 in FY1990 and the minimum was 13,915 in FY2009. The multifactor productivity index (MFP) (2012 = 100) averaged 92.10 over the sample, with a minimum of 79.82 in FY1991 and a maximum of 103.24 in FY2018. Our *Supply* proxy (the standardized ratio of NIST's laboratory R&D to NIST's total R&D), averaged 0.60 over the sample, with a low of 0.35 in FY1995 and a high of 0.997 in FY1990.

Table 4. Descriptive statistics (n = 30)

Variable	Mean	Standard deviation	Minimum	Median	Maximum
SRMs	17,623	3,037	13,915	16,365	24,349
Trend	15.50	8.80	1	15.50	30
LabBudget	508.83	144.80	79.82	495.70	103.24
MFP	92.10	8.18	79.82	94.48	103.24
Supply	0.60	0.15	0.35	0.58	0.99

Table 5. Regression results (robust standard errors in brackets)

	SRM demand	SRM demand
Panel (a): Linear Specification		
Trend	− 5.44	3.23
	[10.34]	[11.32]
ΔLabBudget	–	10.64**
		[4.86]
ΔMFP_{t-1}	347.97**	469.73**
	[162.76]	[227.41]
Supply	661.28***	583.54***
	[99.74]	[149.47]
Constant	− 3109.79***	− 3229.71***
	[478.68]	[622.33]
Observations	30	29
Panel (b): Poisson Specification		
Trend	0.00	0.00
	[0.01]	[0.01]
ΔLabBudget	–	0.004*
		[0.002]
ΔMFP_{t-1}	0.16*	0.22**
	[0.09]	[0.11]
Supply	0.27***	0.27**
	[0.06]	[0.11]
Constant	6.52***	6.38***
	[0.35]	[0.46]
Observations	30	29

***$p < 0.01$, **$p < 0.05$, *$p < 0.1$

Table 5 presents coefficient estimates from the SRM demand equation represented above as Eq. (4). Panel (a) shows the results from estimating the linear equation by OLS, and Panel (b) shows the results from estimating the Poisson regression by MLE. Heteroskedasticity and autocorrelation consistent (HAC) standard errors are reported in brackets. In both cases, SRM demand has a positive and statistically significant relationship with SRM supply and the lagged multifactor productivity index. However, both specifications report a statistically insignificant relationship with the time trend used for proxying SRM prices.Footnote25

Specifically, the results for the linear specification in Panel (a) imply that SRM demand decreases, on average, by 5.44 units ever year.Footnote26 This negative relationship is expected and supports the notion of proxying for price with a time trend. A one unit increase in the multifactor productivity index implies a significant 348 unit increase in SRM units sold the following year, holding all other variables (including supply) constant. This finding suggests that firms increase demand for SRMs when productivity is increasing. Finally, an increase of one standard deviation in Supply is associated with a statistically significant 661 unit increase in SRM units sold.

The results in Panel (b) from the Poisson specification are consistent with those in Panel (a). The estimated relationship between SRM demand and the time trend is zero and statistically insignificant. An increase in the previous year's multifactor productivity index once again leads to a statistically significant increase in SRM demand.Footnote27 Lastly, a positive relationship, significant at the 0.01-level, is again estimated between the demand for SRMs and *Supply.*

We also considered an alternative specification to Eq. (4). We added an additional regressor, ΔLabBudget.Footnote28 In this specification we are not only holding constant, through the variable Supply, the greater the ability of a laboratory to justify a new or expanded research agenda; but also, we are holding constant the ORM's financial ability to supply additional SRMs. The coefficient estimates from this specification are also presented in Table 5. The results are similar, as this specification also shows that an increase in the previous year's multifactor productivity index leads to a statistically significant increase in the market demand for SRMs.

4 Discussion of the findings and future research

There are three important points to emphasize from the statistical analysis above. First, from a policy perspective, the statistically significant coefficient estimates on Supply indicate the economic importance of Congress not only maintaining but in fact also increasing NIST's laboratory R&D budget. An increase in NIST's laboratory budget, relative to the agency's total operating budget, is positively associated with the aggregate demand, and hence use, of SRMs. And, as Link and Scott (2012) have shown, the social rate of return to the use of NIST's metrology is high.

Second, the statistically significant coefficient estimates on the multifactor productivity variable, ΔMFPt-1, indicate that SRM demand is higher following periods of rising multifactor productivity. This result holds whether the estimated demand equation is specified as a linear or Poisson regression. Thus, these findings favor the hypothesis of an income effect of economic activity on the demand for SRMs.

Third, additional research is needed on other documentary standards-related outputs not only from NIST but from the national metrology institutes in other countries. In particular, Fig. 2 suggests that an analysis of the demand for specific SRMs is needed to understand more fully the economic role of SRMs. Along these lines, there is within the literature a conspicuous void of information on the diffusion process of SRMs within organizations. Case studies would be a method that researchers could use to document not only the timing of the diffusion process but also the economic benefits associated with standards in the various stages of production. The development of new metrics on the latter are needed from a policy evaluation perspective.Footnote29

While, to the best of our knowledge, the analysis presented in this paper is the first to estimate the U.S. domestic market demand for SRMs, it is also the first to advocate estimating the market demand for other standards-related outputs (Link, 2021a). Such studies seem to be critical from a policy perspective not only because of the level of national investments in metrology—NIST's total FY2021 budget is $1.04 billion—but also because of the sizeable social impact of measurement standards.

Notes

1. See, https://www.nist.gov/srm/about-nist-srms.

2. As stated in the Act: "The National Bureau of Standards since its establishment has served as the Federal focal point in developing basic measurement standards and related technologies, has taken a lead role in stimulating cooperative work among private industrial organizations in efforts to surmount technological hurdles, and otherwise has been responsible for assisting in the improvement of industrial technology … It is the purpose of this Act to rename the National Bureau of Standards as the National Institute of Standards and Technology [NIST] and to modernize and restructure that agency to augment its unique ability to enhance the competitiveness of American industry …".

3. The National Institute of Standards and Technology (NIST) is the national metrology institute of the United States, and it is administratively located in the U.S. Department of Commerce. A brief institutional history of NIST is in Link (2021b); a more complete and detailed history of NIST is in Cochrane (1966) and Schooley (2000). A brief discussion of the national metrology institutes in other countries is in Link (2021a). It is also appropriate to refer to NIST as a federal laboratory. Federal laboratories, which are government owned (GO), can be distinguished by the characteristic of the laboratory's operational management. Federal laboratories can be government operated (GO) or contractor operated (CO). Thus, federal laboratories are referred to either as GOGO laboratories or GOCO laboratories. NIST is a GOGO laboratory. See https://www.ncbi.nlm.nih.gov/books/NBK568355/.

4. An excellent history of the activities related to the NBS's and NIST's role in the development and maintenance of Standards Reference Materials is by Rasberry (2003).

5. See https://www.nist.gov/mml/orm. See also National Academies (2021) for an evaluation of the ORM and other offices and divisions in NIST's Material Measurement Laboratory.

6. This aspect of technology transference has yet to be studied in the literature (Link and Oliver, 2020).

7. The so-called traditional technology transfer mechanisms that are generally studied are patents, patent licenses, and CRADAs (Cooperative Research And Development Agreements) (Link and Oliver, 2000). The European Commission (2020) makes the case that traditional technology transfer mechanisms fall under the umbrella of knowledge transfer mechanisms.

8. This section has benefitted from information provided by the ORM at NIST and from Leech and Belmont (2000).

9. This section has benefitted from information provided by the ORM at NIST and from Link (1997).

10. Radiopharmaceuticals cannot be sold online. There is no public information about the price of the SRMs listed in Table 1.

11. This section has benefitted from information provided by the ORM at NIST, and from Martin, Gallaher, and O'Connor (2000).

12. Excessive exposure to SO2 can lead to a buildup of fluid in the lungs (pulmonary edema) and possibly to death (Martin, Gallaher, and O'Connor, 2000).

13. See, https://www.nist.gov/system/files/documents/2021/02/16/2021SRMCatalog_WEB.pdf.

14. Using a three-year moving average, we observe a 25% decrease in U.S. SRMs sold between 1990 and 2000, a 12% decrease in U.S. SRMs sold between 2000 and 2010, and a 2% increase in U.S. SRMs sold between 2009 and 2019.

15. More details about these writings of Smith and Marshall are in Swann (2009) and Link (2021a, 2021b). John Quincy Adams, the sixth president of the United States, wrote in 1821, as quoted by Richardson (1976, p. 1): "Weights and measures may be ranked among the necessaries of life … They are necessary to every occupation of human industry … to every transaction of trade and commerce … [K]nowledge of them, as in established use, is among the first elements of education, and is often learned by those who learn nothing else, not even to read and write."

16. Excellent reviews of this literature are in Birch (2003), Lambert (2010), Blind et al. (2011), Robertson and Swanepoel (2015), and King et al. (2017).

17. See also Blind and von Laer (2022).

18. Many of the U.S. case studies were supported by NIST. See Link and Scott (2012) and Tassey (2017). These studies generally did not take into account the econometric issues associated with an analysis of time series data, but we do as we discuss below.

19. Considering the literature reviewed above, and in light of the structure of Eq. (1), one might point out that the multifactor productivity index used to estimate Productivity or MFP is an endogenous variable. To minimize such concerns, we include the multifactor productivity index in the regression specification with a one-year lag as discussed below. Moreover, SRMs represent only a small part of NIST's overall activity, and the measurable impact of SRMs on an aggregate multifactor productivity index is thus minimal.

20. As explained below, the lack of an aggregate price index for SRMs necessitates the use of a proxy variable.

21. We thank those in the ORM at NIST for verifying this proxy variable.

22. A time series is stationary if its first two moments do not depend on the time at which it is observed. Stationarity is required, as a regression of nonstationary time series can lead to spurious results which do not reflect a meaningful underlying relationship.

23. Poisson regression requires that the outcome variable consists of positive integers. We therefore adjust the differenced series of SRM units sold by adding the absolute value of the series minimum, plus one, to each observation.

24. Data are not available for the calculation of the variable Supply for FY1988 and FY1989.

25. We also considered a specification differencing Trend, in which case β1
26. ΔTrend collapses into the constant. As expected, the estimated coefficients on ΔMFP and Supply are little changed.

27. However, the estimated coefficient on Trend is not significant at a traditional level. When the price proxy, Trend, is replaced with a Producer Price Index, the estimated coefficient is also insignificant.

28. The coefficients in Panel (b) can be interpreted as the difference in the logs of expected counts following a one-unit change in the right-hand-side variable. Though less intuitive, the key point is that the estimated coefficients are of the same sign and significance as in Panel (a).

29. An ADF test fails to reject the null implying nonstationarity for the level of LabBudget but confirms that the first difference ΔLabBudget is stationary. Due to this first differencing, the estimation sample shrinks by one observation when ΔLabBudget is included as a regressor.

30. See Hall (2022) as an example of the use of evaluation metrics. See Feller (2022) for an evaluation discussion.

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