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Productivity of Nanobiotechnology Research and Education in U.S. Universities

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Abstract

The National Science Foundation (NSF) estimates that nanotechnology will become a trillion-dollar industry by 2015 and that 800,000 workers will be needed in this field in the United States. Nanobiotechnology — the interface of nanotechnology and the life sciences — is one of the most active and promising application frontiers in nanotechnology. To assess the productivity of university basic and applied research and education in this field, I construct a structural model composed of a system of three equations which respectively represent the productions of a university's scientific publications, patents, and graduate training outputs. The model is estimated using a unique data set on thirty universities that participated in nanobiotechnology during the 1990-2005 period. Ten of them are land-grant universities, ten are non-land-grant pubic universities, and ten are private universities.

Universities indeed serve as a principal seedbed for future development of the cutting-edge nanobiotechnology. NSF investment in nanobiotechnology significantly affects the university's basic science research and graduate education. The university's research expenditures in life sciences, engineering, and physical sciences contribute to its nanobiotechnology fields. Importantly, there is no evidence that research and graduate training compete strongly with one another. Rather, basic science research and graduate education serve as strong complements to one another, basic science and applied research, and applied research and graduate education both serve as weak complements for one another. Ceteris paribus, non-land-grant public universities and universities without medical school or hospital are more efficient in patent production. Presence of a nanotechnology research center on campus enhances the university's basic science research and a formal nanotechnology education program promotes the university's graduate education.

Productivity of Nanobiotechnology Research and Education in U.S. Universities

Overview of Nanotechnology and Nanobiotech

Nanoscale science and technology (hereinafter referred to as nanotechnology) deals with the observation, measurement, and manipulation of matter at the length scale of approximately 1-100 nanometers. The goal of nanotechnology is to create and subsequently utilize functional nano-sized materials that have properties entirely different from their bulk counterparts and thus provide unprecedented capabilities in basic scientific research and novel device and system design. Nanobiotech — one of the most active and promising application frontiers in nanotechnology — lies at the interface of nanotechnology and the life sciences. Whereas nanotechnology offers new concepts, tools, and materials to characterize and transform biosystems, life science presents unique examples of natural functional nanostructures including DNA and protein to guide the synthesis of new nanomaterials and the assembly of new nanodevices (Whitesides).

Today, it is widely believed that nanotechnology has the long-term potential to change our economy as profoundly as did the transistor and the internet (Roco and Bainbridge). The National Science Foundation (NSF) estimates that nanotechnology will become a trillion-dollar industry by 2015 and that 800,000 workers will be needed in this field in the United States. Recognizing nanotechnology's promise as one of the driving forces of technical innovation and economic growth, the U.S. government launched the National Nanotechnology Initiative (NNI) in 2000 to coordinate multiple federal agencies' nanoscale research and development programs. Indeed, U.S. federal investment in nanotechnology has increased more than eightfold in the past seven years, from $116 million in 1997 to $961 million in 2004. These investments support not only individual research projects but also multidisciplinary research centers and education programs. In particular, the proportion of these investments devoted to nanobiotech has risen from around 10 to 15 percent between 2000 and 2003 to 25 percent in 2004.

While commercial products from nanotechnology are already reaching the market, most applications are still at the concept level, requiring much more basic research before they can be incorporated into viable products. Until that takes place, the private sector will not invest in this risky and costly enterprise. Consequently, public funding for university basic research and early-stage development in nanotechnology is critical for creating the scientific base and for preparing a new generation of qualified workers for future nanotechnological development.

Besides federal funding, state and local government funding and policies play an increasingly significant role in university research/education performance in nanotechnology. Having identified nanotechnology as the next growth industry, nearly every economic center has developed an interest in it and some of them have made large commitments toward nanotechnology research. Take Missouri as an example. Although it ranks low nationwide in economic development from nanotechnology (Lux Research Inc.), it recently began focusing on nanobiotech in order to leverage its unique strength in traditional life science. Nanobiotech also has become one of the top research thrusts at the University of Missouri. The state-of-art Life Sciences Center at the University of Missouri provides a common platform for the incorporation of nanotechnology into biotechnology and the life sciences. Multidisciplinary research and education efforts such as the Nanotechnology Initiative Program are well underway and the establishment of a campus-wide or University of Missouri System-wide nanotechnology center is under discussion.

Economics Literature on University Research and Education

Recognizing the private sector's heavy reliance on basic science, economists have long sought to measure the economic contribution of university research. For example, some economists have explored the relationship between university research expenditures and either commercial product output or multifactor productivity growth (Adams). Some have concentrated on university research expenditures as an input to firms' innovation rates (Jaffe), while others have investigated the geographical proximity of private firms to leading university scientists (Zucker, Darby, and Brewer; Darby and Zucker).

Another line of economic study of university research focuses on the input-output relationship in the research process itself, employing the knowledge production function framework pioneered by Zvi Griliches in the late 1960s. Knowledge inputs in such a framework, chiefly intellectual human capital and economic resources, serve to produce knowledge outputs. As universities traditionally have been dedicated to free dissemination of research results, scientific publication has most often been used as the output indicator. For example, Adams and Griliches examined the research performance of U.S. universities in eight broad scientific fields. Elasticities of publication with respect to research expenditure were below unity in all fields, implying decreasing returns. More recently, Xia and Buccola studied the impact of universities' life science budgets on the quantity of their publications cited in agricultural biotechnology patents and on their bioscience graduate training. Publication numbers and graduate training showed, respectively, increasing and decreasing returns to budget scale, and a graduate program's quality ranking had a positive impact on research and training.

With the recent trend toward privatization of research findings, economists have begun analyzing university production of proprietary knowledge outputs, often measured through patents. For example, Foltz, Kim, and Barham examined the production of agricultural biotechnology patents in 100 U.S. universities, concluding that the Land Grant infrastructure and previous patent success significantly affect a university's patent output. These studies focus on the production of only one research output, either publication rate or patent count. In fact, university research tends to produce both outputs, and generating one may well affect the other on account of resource limitations and the strong connection between science and technology. Another complicating factor is the graduate education of the science and engineering workforce, which is closely related to universities' research activities but has not been explicitly modeled in most economic studies.

Econometric Model

To comprehensively assess the productivity of university basic and applied research and education in nanobiotechnology, I construct a structural model composed of a system of three equations which respectively represent the productions of a university's scientific publications, patents, and graduate training outputs. The model is outlined below. All variables refer to nanobiotech unless otherwise indicated. In a given year at a given university, let

S	be the quantity of basic research output measured by scientific publications;
P	the quantity of applied research output measured by patents;
G	the number of Ph.D. students trained;
E_{life}, E_{engr}, E_{phy}	R&D expenditures in the life sciences, engineering, and physical sciences respectively;
E_{nano}	R&D expenditures in nanotechnology awarded by federal agencies;
RK	quality ranking of relevant science and engineering programs;

Pubpriv	the public/private status of a university (1=public, 0=private);
Land	the land-grant identity (1=landgrant, 0=non-land-grant);
Hosp	the presence of a university hospital (1=with hospital, 0=without hospital);
Med	the presence of a medical school (1=with medical school, 0=without medical school);
CTR	presence of a multidisciplinary nanotechnology research center (1=with a center, 0=without a center);
S_{stock}	university knowledge stock, measured by the discounted accumulation of scientific publications from previous years;
TTO	a vector of the university Technology Transfer Office's (TTO) characteristics, including its operating budget, staff size, and previous patenting and licensing success;
EDU	presence of a formal multidisciplinary nanotechnology education program (1=with a education program, 0=without an education program).

A university's basic and applied nanobiotech research and graduate-training production functions can then be specified as:

(1) $S = f\left(P, G, E_{life}, E_{engr}, E_{phy}, E_{nano}, RK, RK * E_{nano}, Pubpriv, Land, Hosp, Med, CTR, S_{stock}\right)$

(2) $P = f\left(S, G, E_{life}, E_{engr}, E_{phy}, E_{nano}, RK, RK * E_{nano}, Pubpriv, Land, Hosp, Med, CTR, TTO\right)$

(3) $G = f\left(P, S, E_{life}, E_{engr}, E_{phy}, E_{nano}, RK, RK * E_{nano}, Pubpriv, Land, Hosp, Med, CTR, EDU\right)$

where time subscripts and lag operators are, for notional simplicity, suppressed. These three equations appear simultaneous. Research and graduate training serve as inputs to one another:

students assist with their professors' research programs, and experience with a professor's research in turn is an essential element in a student's education. At the same time, research and education compete for the professor's time and other resources. Model (1) – (3) allows for such interactions, so that synergies or tradeoffs among articles, patents, and graduate student training can be assessed.

Since resources are poorly allocable between research and graduate training, the same R&D expenditure variables are included in all three production equations. In equation (1), derivative $\partial S / \partial E_{nsfnano}$ reflects the marginal products of the NSF R&D investments in basic nanobiotech research, i.e., by how much an additional dollar of R&D investment increases scientific publications and elasticity associated with the derivatives indicate the returns of basic research to budget scale. Marginal products of R&D investments and returns to budget scale — two measures of returns to R&D investments — in applied nanobiotech research and graduate training can be derived similarly from equations (2) and (3), respectively.

University nanobiotech success depends on factors beyond the budget directly devoted to it. First, a university's research efforts in other fields such as the life sciences, engineering, and physical sciences may contribute to its nanobiotech program. This contribution is represented by the partial derivatives of the left-hand-side output variables with respect to R&D expenditures in those fields. Second, university research and education in nanobiotech likely are affected by prior conditions of its nanobiotech-related programs, which can be measured by relevant science and engineering program rankings. Higher-ranked universities attract higher-quality professors and graduate students and hence can produce more output with a given budget. Furthermore, higher program rankings can indirectly contribute to output by enhancing the research and education products of another dollar of R&D expenditure. Such enhancements are found by differentiating the respective marginal products of R&D expenditures with respect to program ranking, which are represented by the coefficients of the cross terms between R&D expenditures and program rankings in model (1) - (3). Third, a university's public/private status and land-grant identity may impact its orientation toward basic research, applied research, and student training. Fourth, nanobiotech research is highly interdisciplinary. The presence of a multidisciplinary nanotechnology research center would facilitate information flows, foster collaborative research relationships among faculty from different disciplines, and provide students with opportunities to gain hands-on experience in laboratories other than their major professors'. Finally, three variables are employed in structural equations (1) - (3) as identifying variables, respectively indicative of (i) the university's science base in nanobiotech upon which its faculties can further pursue their scientific inquiries, (ii) its technology transfer capacity, and (iii) its intensity in nanotechnology teaching.

Data

Research universities are sorted into three strata — land-grant universities, non-land-grant public universities, and private universities. Annual data are collected from a random sample of ten universities in each stratum that participated in nanobiotech from 1990 to 2005. The following broad sets of life-science keywords are constructed and used jointly with "nano" to search for data in nanobiotech field from various sources:

nano$ and (bio$ or DNA or RNA or genetic$ or protein or patholog$ or bacteria$ or fungus or fungi or metaboli$ or enzyme or physiology$ or entomolog$ or ecolog$ or human or medic$ or cancer or blood or immunolog$ or pharmac$ or toxicolog$ or neuron$ or agricult$ or animal$ or livestock or aquatic$ or crop$ or veget$ or fruit$ or food$)

Using the above keyword set, I first draw scientific publications in nanobiotech authored by each university in each year from ISI's *Science Citation Index Expanded*. I then draw nanobiotech patents awarded to each university in each year from the U.S. Patent Office database. Although a new patent class for nanotechnology was created in 2004, all previously issued patents belonging to this class may not have been re-classified to it. Nanobiotech patents therefore have to be identified by applying the keyword set. Data on graduate students trained in nanobiotech at each of the 30 sample universities are obtainable from *Dissertation Abstract*, a source covering graduate theses accepted at all accredited U.S. institutions. The keyword set is employed to search for nanobiotech theses by year and university, indicating the numbers of Master's and Ph.D. degrees awarded in this field.

Federal agencies committing significant investments to nanobiotech include the National Institutes of Health (NIH), National Science Foundation (NSF), U.S. Department of Energy (DoE), U.S. Department of Defense (DoD), and U.S. Department of Agriculture (USDA). In principle, search for life-science and nanotechnology keywords will filter out sponsored nanobiotech research projects in each agency's award record database. Each university's nanobiotech R&D expenditures from the federal government can then be derived. Unfortunately, all federal agencies except NSF do not maintain award record databases that are searchable by keywords and hence, data on federal supports for a university's R&D in nanotechnology can only include those from NSF. Annual data on university R&D expenditures in the life sciences, engineering, and physical sciences are directly available from NSF's WebCASPAR database.

Data on graduate program ranking and other university fixed factors such as public-private status, land-grant identity, and presence of university hospital and medical school are provided by the *Gourman Report* and the U.S. Department of Education. Lists of nanotechnology research centers and educational programs sponsored by the federal government are available from NNI. These are cross-checked and complemented by a search of each university's website. Information on institutional characteristics of university TTOs is available from the Association of University Technology Transfer Managers' (AUTM) annual report.

Descriptive statistics are presented in Table 1. Data on research and education outputs of each university between 1990 and 2005 are provided in Table 2. Annual breakdown of these outputs are reported in Table 3. The thirty sample universities generated a total of 3088, 1507, and 705 publications, patents, and PhD degrees in nanobiotechnology respectively during the whole study period. Very few Master's degrees were awarded. All the thirty universities' publications together increased from 6 in 1990 to 723 in 2005. During the same period, their patents grew from 28 to 162, while total number of PhD graduates jumped from 10 to 179.

Results

In the empirical estimation, a variety of temporal patterns in the basic research, applied research, and graduate education equations, including distributed lags as well as finite lags on individual factors, are examined. The three equations (1)-(3) can be fitted alternately with OLS, SUR, a fixed-effects estimator, and a GLS model. Single-equation estimates in table 4 have R^2 s respectively at 0.67, 0.49, and 0.61 for the three equations, rather high considering the wide variety of sample universities.

NSF investment in nanobiotechnology significantly affects the university's basic science research and graduate education, but the effects are small with sample-mean elasticities of 0.06% and 0.16%, respectively. NSF funding has nonsignificant effect on the university's patent numbers. The university's R&D expenditures in life sciences has a strong positive effect on it's basic and applied research: a one-percent increase in life science R&D induces a 0.35% and 1.18% increases in university scientific publications and patents. The university's research expenditures in physical sciences and engineering respectively has a strong positive effect on it's applied research and Ph.D. training. Every one-percent increase in physical sciences and engineering R&D respectively leads to a 0.23% and 0.27% increase in patents and Ph.D. degrees awarded.

Importantly, there is no evidence that research and graduate training compete strongly with one another. Rather, basic science research and graduate education serve as strong complements to one another, basic science and applied research, and applied research and graduate education both serve as weak complements for one another.

Ceteris paribus, non-land-grant public universities and universities without medical school or hospital are more efficient in patent production than their land-grant and private counterparts and those with medical school and hospital. Such characteristics of universities, however, do not significantly affect the universities' efficiencies in basic research and graduate education. Presence of a nanotechnology research center on campus enhances the university's basic science research and a formal nanotechnology education program promotes the university's graduate education.

Discussions

As an enabling or platform technology, nanotechnology has extraordinary potential to enhance innovation, technical change, and productivity growth in a wide variety of industries, helping to maintain the competitiveness and sustainability of the U.S. economy.

Nanobiotechnology is one of the most active and promising application frontiers in nanotechnology.

Universities indeed serve as a principal seedbed for future development of the cutting-edge nanobiotechnology. Empirical results in the present study shed light on the productivity effects of public investment and policy choices in university nanobiotechnology research and education. For example, the results indicate significant returns to federal investments in nanobiotech itself as well as the contributions of R&D expenditures devoted to related fields. They illustrate which types of university, public or private, land-grant or non-land-grant, with hospital and medical school or without, make more efficient uses of resources for basic research, applied research, and graduate student training. They demonstrate that a nanotechnology research center or formal nanotechnology education program is justified.

Table 1. Descriptive Statistics

Variable	Max	Min	Mean	St. Dev
Publications	59	0	6.43	8.55
Patents	28	0	3.14	4.14
PhD degrees	22	0	1.47	2.30
Eng. R&D (million $)	381.38	1.22	56.94	62.76
Phy. sci. R&D (million $)	150.56	0	28.48	27.39
Life sci. R&D (million $)	596.53	0.55	160.45	121.41
Nano R&D (million $)	61.73	0	2.65	5.73

Table 2. Publications, Patents, and Ph.D. Degrees Awarded in Nanobiotechnology: University Totals Between 1990 and 2005

Institution	Publications	Patents	PhD degrees
Case Western Reserve University	44	27	8
Columbia University	70	58	18
Cornell University	148	86	55
Georgia Institute of Technology	88	23	17
Harvard University	303	81	33
Johns Hopkins University	121	152	30
Kansas State University	21	9	3
Louisiana Tech University	44	0	15
North Carolina State University	56	63	19
Northwestern University	191	38	38
Ohio State University	104	30	22
Pennsylvania State University	138	0	42
Rice University	65	34	19
Stanford University	133	77	36
Tufts University	41	5	5
University of California-Los Angeles	124	53	31
University of Cincinnati	40	17	17
University of Illinois at Urbana-Champaign	172	42	51
University of Kansas	36	8	13
University of Maryland	159	39	16
University of Michigan	176	149	47
University of Missouri-Columbia	33	12	5
University of New Mexico	18	12	2
University of Pennsylvania	114	96	27
University of Texas-Austin	98	97	21
The University of Utah	64	69	12
University of Virginia	77	37	24
University of Washington	164	68	35
University of Wisconsin-Madison	131	79	28
Washington University	115	46	16
Sum	3088	1507	705

Table 3. Publications, Patents, and Ph.D. Degrees Awarded in Nanobiotechnology: Annual Totals for Thirty Universities

Year	Publications	Patents	PhD degrees
1990	6	28	10
1991	74	25	11
1992	62	43	10
1993	69	31	21
1994	57	37	6
1995	97	47	23
1996	90	58	22
1997	102	93	21
1998	146	118	40
1999	169	137	33
2000	175	119	33
2001	197	114	48
2002	266	151	54
2003	360	150	85
2004	495	194	109
2005	723	162	179
Sum	3088	1507	705

Table 4. University Production of Publications, Patents, and Ph.D. Degrees in Nanobiotechnology: Parameter Estimates

	Publications		Patents		PhD degrees	
Variable	Estimate	t	Estimate	t	Estimate	t
Intercept	-2.304	-1.92	-0.583	-0.81	-1.584	-3.02
Publications			0.055	1.98	0.153	13.32
Patents	0.145	1.93			0.032	1.45
PhD degrees awarded	1.759	13.61	0.198	2.11		
Eng. R&D	0.000	0.02	0.002	0.38	0.007	3.38
Phy. sci. R&D	-0.003	0.21	0.025	2.66	-0.006	-1.33
Life sci. R&D	0.014	3.41	0.023	8.26	-0.001	-0.92
Nano R&D	0.136	2.54	0.006	0.15	0.086	5.33
Pubpriv	-0.249	-0.30	1.535	3.13	0.439	1.69
Land grant	-0.243	-0.35	-1.858	-4.51	-0.134	-0.64
Hospital	-1.125	-1.74	-0.927	-2.38	0.073	0.37
Med School	-0.188	-0.19	-1.100	-1.88	0.956	2.14
Nano center	1.389	2.37	-0.692	-1.96	0.308	1.72
Time trend	0.451	6.89	0.099	2.44	0.049	2.48
Nano ed. program					0.874	2.54
R^2	0.67		0.49		0.61	

References

Adams, J. (1990). "Fundamental Stocks of Knowledge and Productivity Growth." *Journal of Political Economy* 98: 673-702.

Adams, J. and Z. Griliches (1996). "Research Productivity in a System of Universities." NBER Working Paper No. 5833.

Darby, M. and L. Zucker (2003). "Grilichesian Breakthroughs: Inventions of Methods of Inventing and Firm Entry in nanotechnology." NBER Working Paper No. 9825.

Foltz, J., K. Kim, and B. Barham (2003). "A Dynamic Analysis of University Agricultural Biotechnology Patent Production." *American Journal of Agricultural Economics* 85: 187-197.

Jaffe, A. (1989). "Real Effects of Academic Research." *American Economic Review* 79: 984-999.

Lux Research Inc. (2005). *Benchmarking U.S. States for Economic Development from Nanotechnology*.

Roco, M. and W. Bainbridge (2001). *Societal Implications of Nanoscience and Nanotechnology*. Kluwer Academic Publishers, Boston, MA.

Whitesides, G. (2003). "The 'Right' Size in Nanobiotechnology." *Nature Biotechnology* 21: 1161-1165.

Xia, Y. and S. Buccola (2005). "University Life Science Programs and Agricultural Biotechnology." *American Journal of Agricultural Economics* 87: 229-243.

Zucker, L., M. Darby, and M. Brewer (1998). "Intellectual Human Capital and the Birth of U.S. biotechnology Enterprises." *American Economic Review* 88: 290-306.