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Time substitution and network effects with an application to nanobiotechnology policy for US universities

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ABSTRACT

We present a dynamic network model of the knowledge production process for nanobiotechnology research at 25 US universities during 1990–2005. Universities produce knowledge outputs in nanobiotechnology consisting of Ph.D. graduates, research publications, and patents. Inputs include the university's spending on R&D in engineering and the life sciences, and the university's own stock of knowledge measured by past publications in nanobiotechnology. In addition, universities take advantage of the stock of knowledge produced by other universities in previous periods. We simulate the effect of the National Science Foundation being able to optimally allocate research funds for nanobiotechnology research between universities and across time so as to maximize the aggregate amounts of the three knowledge outputs produced by the universities.

1. Introduction

Gordon [1] identifies three industrial revolutions comprising first, steam and railroads, second, electricity, indoor plumbing, communications, and the internal combustion engine, and third, computers, the internet, and mobile phones. However, economic growth has slowed since the middle of the twentieth century and Gordon predicts that the bottom 99% of the income distribution might experience growth of less than one half of 1% in the coming decades.

Although science and research and development of all forms have been responsible for a large proportion of past economic growth, recent federal spending on science and private spending on research and development as a percent of GDP has fallen from about 1.25% in 1976 to approximately 1% in 2009 (Economic Report of the President [2]). One beacon of light has been in the area of nanotechnology. Between 2001 and 2008 the number of inventions in nanotechnology and the number of nanotechnology workers grew at a 25% annual rate, with the worldwide nanotechnology product market reaching $254 billion in sales in 2009 (Roco et al. [3]). The National Science Foundation estimates that nanobiotechnology could become a trillion dollar industry employing more than 800,000 workers by 2015. In this paper we examine science spending for nanobiotechnology research and education at 30 US universities during the period 1990 to 2005. Weber and Xia [4] estimated inefficiency and Morishima elasticities of output substitution for nanotechnology research publications, Ph.D. students, and patents using a stochastic directional distance function. We extend their research in an effort to shed light on two important questions. First, can a reallocation of resources between different universities enhance the university outputs of research, patents, and Ph.D. graduates? If some universities are consistently on the cutting edge of the research frontier then reallocation of resources away from non-frontier universities towards frontier universities could enhance productivity. On the other hand, scale diseconomies might limit the extent of the efficiency gains from reallocating resources. Second, can resources be reallocated across time to enhance productivity? Here, we want to investigate whether it is better for federal agencies to allocate research dollars early in the development stage of new technologies, later in the development stage, or more or less continuously throughout the period.

To investigate these questions we integrate two recent methods using data envelopment analysis: dynamic network production and time substitution. We assume that universities form a network in producing students, research papers, and patents in nanobiotechnology. Changes in the allocation of resources within the network have the potential to enhance productivity. In addition, if the choice were available, each individual university might choose to spend more in a current period by borrowing from a future period so as to maximize production across all periods. Alternatively, individual universities might save resources so as to expand future production. However, to the extent that production by one university in a particular period

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has an effect on the output possibilities of other universities, such a unilateral reallocation might not be Pareto improving. For instance, the accumulation of knowledge often moves in small steps so that if a single step is removed, the process might go down a different path, or stagnate. Thus, we want to account for the fact that research papers written by one university in a given period spill over to other universities in subsequent periods. The idea of knowledge spillovers can be represented Isaac Newton's famous quote: "If I have seen further it is by standing on the shoulders of giants" (op cit. Merton [5]).

Given the potential for knowledge spillovers between universities, coordination of resources between universities and across periods might allow an expansion in production possibilities. To the extent that government agencies already attempt to solve such a problem, any findings of inefficiency in the network might be attributed to the transaction costs associated with acquiring information and providing the proper incentives to the producers to enhance output.

2. Economic returns to science research

The latter part of the 1970s saw the US undergo a period of stagflation. From 1962 to 1976 annual labor productivity growth averaged 2.5% but fell to only 0.5% during 1976 to1980 (Economic Report of the President [2]). Concerns about slow productivity growth led Congress to pass the Bayh–Dole Act in 1980. This Act allowed universities to patent and license research results that had been subsidized through federal funding. Before passage of the Bayh–Dole Act, any inventions that grew out of federally sponsored research became property of the federal government. The Act was not without its critics as some people argued that university research might switch focus from basic research to applied research. For instance, Boldrin and Levine [6] and Just and Huffman [7] presented models showing that when universities are granted monopoly power via patents, the production of new knowledge falls as resources are reallocated toward industrial applications. Weber and Xia [4] found supporting evidence for this theory in the university production of nanobiotechnology patents and publications. Using estimates of the Morishima elasticities of transformation, Weber and Xia [4] found that when the quantity of patents increases relative to publications, the shadow revenue share of publications falls relative to patents. However, other researchers found that university patenting activities tended to complement, rather than substitute for basic research (Thursby and Thursby [8], Azoulay et al. [9], Fabrizio and DeMinin [10]).

One rationale for the public funding of research is that knowledge is a public good – both non-rival and non-excludable – and will be under-produced in private settings since private actors cannot fully capture its returns. Adams [11] presented evidence indicating a time lag of 15 to 20 years between the production of basic research and its embodiment in new technologies. He also suggested that about 15% of the productivity slowdown in the 1970s could be attributed to World War II which siphoned scientists and engineers into the war effort. In a thorough review of the literature on the economic benefits of private and publicly funded basic research Salter and Martin [12] cite evidence that the social returns to private R&D spending tend to be 2–5 times higher than the private returns. In addition, they identify six categories that embody the economic returns to publicly funded research: new knowledge, more skilled workers, new scientific instruments, enhanced network effects and social interactions between researchers and the private sector, an increased capacity to solve new problems, and new firms spawned by the research. To measure potential spillovers from agricultural R&D on agricultural productivity Plastina and Fulginiti [13] estimated a stochastic cost function for 48 states during the 1949–1991 period. Costs are dependent on the state's own R&D stock and the stock of R&D from adjacent states with increases in R&D from neighboring states causing declines in the own state's costs of production. The findings indicate an average 17% internal rate of return for the state's own R&D funding and a 29% social rate of return.

3. The knowledge production process

Various researchers have developed network models of producer performance and models that measure dynamic performance by examining the allocation of resources over multiple periods. Färe and Grosskopf [14] developed a dynamic measure of firm performance where decision-making units determine the amounts of a final output and an intermediate output (capital) to maximize production over multiple periods. Nemoto and Goto [15,16] derived dynamic optimality conditions so that overall producer efficiency can be decomposed into static and dynamic efficiencies. Tone and Tsutsui [17], Fukuyama and Weber [18] and Akther et al. [19] develop a network performance indicator where producers in a first stage of production use exogenous inputs to produce an intermediate output that becomes an input to a second stage of production where final outputs, including an undesirable output are produced. In their model the past production of the undesirable output shrinks the current period's production possibility set. Fukuyama and Weber [20,21] account for the possibility that in the second stage of production a second intermediate output can be produced in lieu of final outputs so as to expand the production possibility set in a future period. Thus, the performance measure compares the observed use of inputs and production of outputs with the potential outputs that could be produced if resources were allocated efficiently across many periods. Sacoto et al. [22] examine university production where various inputs are used to generate an intermediate output of student internships that become an input in the production of job placements—the final output. Fallah-Fini et al. [23] provide a thorough review of dynamic measures of performance.

In this section and the next we present a dynamic network production model that accounts for the potential for the stock of knowledge created in the past to influence the current production of new knowledge. We assume that production takes place by $k=1, \ldots, K$ universities in $t=0, 1, \ldots, T$ periods. We follow conventional notation and represent vector valued variables in bold face and scalar variables in italics. The $n=1, \ldots, N$ inputs used by university k in period t are represented by $\mathbf{x}_k^t = (x_{k1}^t, \ldots, x_{kN}^t) \in R_+^N$. In the empirical section of the paper we assume that these inputs include real university R&D expenditures in engineering, the physical sciences, and the life sciences. Another input is derived from grants from the National Science Foundation that have been awarded for the study of nanotechnology. Furthermore, universities harness the existing stock of knowledge as an input to help create new knowledge. The universities use these inputs to produce $m=1, \ldots, M$ knowledge outputs represented by $\mathbf{y}_k^t = (y_{k1}^t, \ldots, y_{kM}^t) \in R_+^M$. Our data set allows us to identify three university outputs in the area of nanobiotechnology: publications (y_1), patents (y_2), and Ph.D. graduates in (y_3).

To account for the dynamic process of production we recognize that knowledge produced in the form of publications (y_1) is not lost or sold, but instead becomes an input to the production process in future periods. In addition, university researchers draw not only on their own publications, but on the publications of their colleagues at other universities. The knowledge embodied in publications serves as a spillover input that becomes available to researchers at other universities. It seems reasonable to assume that the stock of past publications generated by the university might have a different marginal effect on the production of new knowledge than the stock of past publications generated by other universities in the same field, since such knowledge might only be tangential to the research and