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Productivity of innovation in biofuel technologies

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ABSTRACT

Biofuels are a regular focus of public policy. The productivity of innovation in biofuel technologies is rarely addressed either in research or policy. Yet as innovation in any field grows complex and costly it can experience reductions in productivity and diminishing returns to investments. We examine here the productivity of investments in the technologies used to produce biofuels, using data from the U.S. Patent and Trademark Office. The results show that the productivity of innovation in biofuel technologies is declining. Continuation of this trend will in time force reductions in research investments in biofuel technologies. We discuss policy approaches to address declining returns to research investments.

1. Introduction

While there has been a steady increase in adding alternative energies to the transport and other sectors, liquid fuels are still highly dependent on fossil energy. Alternative liquid biofuels derived from substances such as sugar cane, corn, jatropha, and algae have one main selling point: They are renewable. While there are significant differences among liquid biofuels in regard to production, all are argued to have a lower environmental impact at both the extraction and consumption stages (Renewable Fuels Association, 2015; Skutsch et al., 2011; Slade and Bauen, 2013). Thus, while biofuels are economically marginal in the marketplace, they are socially and politically useful (Solomon et al., 2007: 422). This makes biofuels a regular target of policies.

Until recently innovation in the biofuel sector was variable year-to-year, and lagged due to the low price of oil, taxes, and subsidies to other energy sectors. In 2008, for example, the biofuels sector received $18 billion in investments, but this declined to $7 billion in 2009 (Costantini et al., 2013: 204). In response to the energy crisis of the 1970s, and the increase in oil prices in the early 21st century, governments enacted policies to encourage or even mandate biofuel production and consumption, and to support research in biofuel technologies. In the United States, the Energy Tax Act of 1978 subsidized ethanol by a tax remission (Solomon et al., 2007: 418). The Renewable Fuels Standard (RFS) in 2005 and 2007 required higher levels of biofuel production and consumption (Costantini et al., 2013: 204; Albers et al., 2016: 814). Of biofuel producing nations, only Brazil is able to maintain a biofuel marketplace without public support (Costantini et al., 2015a: 288–289; Costantini et al., 2015b: 580). All other countries require policy intervention to make biofuels economically competitive. This intervention is mostly through tax policies, as well as through targets and mandatory fuel blending.

Biofuel policies sort into two types: demand-pull and technology-push (Costantini et al., 2015a, 2015b; Kessler and Sperling, 2016). Demand-pull policies specify such actions as mandating specific levels of production or consumption of biofuels, or specific fuel mixes. Technology-push policies support the development or dissemination of biofuel technologies through, for example, support for research and development (R&D). These policy approaches are individually appropriate for different generations of biofuel technologies, as discussed below.

An important area not yet explored in the biofuels literature (e.g., Goetz et al., 2017) is the economic productivity of research inputs, especially innovators, and how that productivity trends over time. It is generally not possible to learn the R&D costs of specific firms (Costantini et al., 2013: 205; Costantini et al., 2015b: 581). This lack of economic input data is important, for globally firms account for 56% of all biofuel innovations (Albers et al., 2016: 817). Therefore a different approach is required. Recently a group of research teams has used patent data to explore the economics of innovation in biofuel technologies, including the effects of policy (Costantini et al., 2013, 2015b; Albers et al., 2016; Kessler and Sperling, 2016).

We extend this research with a recently-developed approach to measuring the productivity of innovation through the study of

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patenting authorship (Strumsky et al., 2010; Tainter et al., 2018). Our purpose is to ascertain the direction of innovation productivity in biofuel technologies, and to suggest policy approaches commensurate with our findings.

2. Background and framework

Innovation in liquid biofuel technologies is part of the industrial world's overall program of scientific and technical research and development. As such, it is subject to the same constraints and developmental pressures as scientific inquiry as a whole. One of these constraints is the complexity of the enterprise, and one of the developmental pressures is the productivity of investments in R&D. Continuous innovation must provide constant or increasing returns to innovative efforts, but complexity can increase the costs of those efforts. Our investments in research and development must yield the results we want. Should this cease to be the case, the incentive to continue to invest in innovation diminishes.

Innovation is a complex system embedded within other complex systems. Complexity is here defined as increasing differentiation and specialization in structure (more parts and more kinds of parts), combined with increasing integration of parts (Tainter, 1988). In the area of innovation, differentiation in structure consists of such elements as the incorporation of multiple departments or firms, or disciplinary specialties, in the research process. Integration is provided by the actions of firms or government agencies to organize innovative activities into a coherent research program. Complex systems have evolutionary histories, and innovation is no exception. Knowledge production, like other human activities, grows complex and produces diminishing returns (Tainter, 1988). As an aspect of knowledge production, innovation grows in complexity and costliness, and exhausts easy solutions to problems. The productivity of innovation is therefore not constant. Research problems over time grow increasingly complex and difficult to solve. In response, research and development grow increasingly complex, and correspondingly more costly (Rescher, 1978, 1980).

In every scientific field, early research plucks the lowest fruit: the questions that are least costly to resolve and most broadly useful. As general knowledge is established early in the history of a discipline, that which remains axiomatically becomes more specialized. Specialized questions become more costly and difficult to resolve. Research organization moves from isolated scientists who do all aspects of a project, to teams of scientists, technicians, and support staff who require specialized equipment, costly institutions, administrators, and accountants. The size of research teams grows, as illustrated in the increasing size of science authorship teams (Wuchty et al., 2007; Jones et al., 2008). Thus fields of scientific research follow a characteristic developmental pattern: from general to specialized; from wealthy dilettantes and lone-wolf scholars to large teams with staff and supporting institutions; from knowledge that is generalized and widely useful to research that is specialized and narrowly useful; from simple to complex; and from low to high societal costs.

Complexity always costs, whether the costs are measured in calories, time, effort, or money. As complexity and costliness increase, diminishing returns inevitably follow (Tainter, 1988). This is as important in R&D as in any other sphere of human activity. It has long been known that within individual technical sectors, the productivity of innovation reaches diminishing returns. Hart (1945) showed that innovation in specific technologies follows a logistic curve: Patenting rises slowly at first, then more rapidly, and finally declines. Rostow (1980: 171) extended this observation in his attempt to explain why economic growth slows in developed countries.

Nicholas Rescher has argued forcefully that innovation as a whole reaches diminishing returns. Paraphrasing Max Planck, Rescher observed that "…with every advance [in science] the difficulty of the task is increased" (1980: 80). Writing specifically in reference to natural science, Rescher suggested:

> Once all of the findings at a given state-of-the-art level of investigative technology have been realized, one must move to a more expensive level…. In natural science we are involved in a technological arms race: with every "victory over nature" the difficulty of achieving the breakthroughs which lie ahead is increased (1980: 94, 97).

Rescher (1978: 79–94) terms this "Planck's Principle of Increasing Effort". Planck and Rescher suggest that *exponential* growth in the size and costliness of science is needed just to maintain a *constant* rate of innovation. Science must therefore consume an ever-larger share of national resources in both money and personnel. Schmookler (1966: 28–29), for example, showed that while the number of industrial research personnel increased 5.6 times from 1930 to 1954, the number of corporate patents over roughly the same period increased by only 23%. Such data prompted Wolfle (1960) to pen an editorial for *Science* titled "How Much Research For a Dollar?" Derek de Solla Price observed in the early 1960s that science even then was growing faster than both the population and the economy and that, of all scientists who had ever lived, 80–90% were still alive at the time of his writing (de Solla Price, 1963). These observations are consistent with the argument that R&D, over time, grows complex and costly and produces diminishing returns. We can also demonstrate this quantitatively, as shown next.

In earlier research we plotted trends in the productivity of research as a whole, and in specific technical sectors (Strumsky et al., 2010; Tainter et al., 2018). We used data from U.S. patents from 1974 to 2012 to measure performance in R&D. About half of U.S. patents are granted to non-U.S. applicants, so the data reflect global innovation. Productivity is measured as patents per author. This is equivalent to the standard measure of productivity in the economy as a whole: output per worker. Additional workers translate to increasing complexity and added costs, so we use number of patent authors as a partial measure of cost. As depicted in Fig. 1, R&D shows that, from 1974 to 2012, the productivity of innovation declined by 22%. Fig. 1 was constructed from a database of over three million patents. Our analyses point to increasing complexity as the reason for this (Strumsky et al., 2010: 505–506; Tainter et al., 2018: 88). Here we extend this line of investigation into productivity in the technologies that are employed to produce liquid biofuels.

3. Methods

Productivity of innovation within a sector or industry is difficult to calculate directly due to the fact that firms consider such information proprietary (Costantini et al., 2013: 205; Costantini et al., 2015b: 581). Therefore alternative methods must be employed to assess productivity in innovation and whether an industry is experiencing diminishing returns to R&D inputs.

For this analysis, an innovation is considered to be a technical novelty that earns a patent. Using the data provided by the United States Patent and Trademark Office (USPTO), we constructed a database of liquid biofuel technologies patented since 1976. To obtain the information necessary for this database, source data were extracted using a method similar to that employed by Lobo and Strumsky (2008) from the USPTO. The information gathered included title, authorship, patent number, technology codes, date patent was requested, and date patent was granted. The data were gathered using a keyword search of terms and patent codes, as described below. This search returned over 11,000 patents from 1901 to 2016.

The USPTO has two technology code classification systems, one that is currently in use, the Cooperative Patent Classification (CPC), and the second that has been largely phased out, the U.S. Patent Classification (USPC). As part of an international effort to harmonize technology codes across intellectual property systems around the world, the U.S. patent office adopted the CPC technology codes for their utility patents and phased out the USPC system that had been in place for decades. The