A Framework for Examining Technical Change

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Abstract. *Technical change is dynamic, recursive, and endogenous to the economic system However, empirical studies usually treat technology as exogenous, defining technical change in terms of its end result changes in some production possibilities set An endogenous view of technical change is necessary to understand, anticipate, and perhaps alter the development and use of new technologies and their associated problems. This article outlines a conceptual framework in which technical change is endogenous The framework accounts for the dynamic and recursive interactions between research and development activities, the adoption and diffusion of new innovations, and the regulatory and institutional environment As an example, the development of glyphosate-tolerant crops is discussed to show how the framework can be used to identify, organize, and understand the important variables and relationships for a specific case of technical change.*

Keywords. *Technical change, research and development, adoption, diffusion, regulation, glyphosate tolerance*

The impact of technical change on economic growth has been well known since Adam Smith's *Wealth of Nations* (*32*) [1] More recently, Solow (*34*) attributed 87 5 percent of the longrun growth in U S output to technical change Although technical change is an important source of economic growth, the use of technology is tied to many existing agricultural and resource problems New technologies will likely help solve these problems while simultaneously creating the next generation of problems For example, the use of chemicals and conventional tillage in agriculture is partially responsible for surface- and ground-water contamination. But new technologies, such as genetically engineered plants with nitrogen-fixing abilities or tolerance to pests, may reduce the need for chemical applications

While technical change is a dynamic and recursive process that is endogenous to the economic system, empirical studies usually treat technology as exogenous, and define technical change in terms of its end result—changes in some production possibilities set An endogenous view of technical change is necessary to understand, anticipate, and perhaps alter the development and use of new technologies and their associated new problems

Economic literature contains many studies addressing technical change as an endogenous component of the economic system Griliches (*10*), Metcalfe and Gibbons (*24*), Hayami and Ruttan (*12*), and Johnson (*14*) have analyzed particular aspects of technical change and, in various ways, have discussed the need for an endogenous view of technical change. Excellent reviews of various aspects of the subject can be found in (*4*, *7*, *15*, *28*, and *35*)

At this time, however, the enormous amount of research in this area has not been integrated into a systematic, cohesive whole The objectives of this article are to (1) present a conceptual framework for examining technical change as an endogenous process that integrates the many individual issues found in the literature, and (2) demonstrate the framework's usefulness in explaining the development of a biotechnology product, namely glyphosate-tolerant crops Glyphosate, sold under such names as Round-Up, a trademark of Monsanto, is a broad spectrum, nonspecific herbicide that kills annual sedges, grasses, and broadleafed plants However, via biotechnology methods, glyphosate can now be applied to certain crops (tomatoes, tobacco, cotton, soybeans, canola) that it would otherwise kill

A Conceptual Framework

This section integrates the key relationships identified in the literature on technical change into a unified conceptual framework by first defining the concepts of technology and technical change We then define major components of technical change, after which the links between each component are discussed in detail

Technology is generally the application of accumulated knowledge in society, and technical change is the application of new knowledge Economists tend to use the term, technology, to describe a relatively specific and discrete way of producing something We follow Mundlack and define a technique according to a

The authors are agricultural economists with the Resources and Technology Division, ERS An earlier version of this paper was presented at the Western Economic Association meetings, Lake Tahoe, NV, 1989 The authors thank the journal editors and reviewers for helpful comments Use of brand names in this article does not constitute endorsement by the U S Department of Agriculture

[1] Italicized numbers in parentheses cite sources listed in the References section at the end of this article

conventional input requirement set and a technology as the convex hull of the technique input requirement sets, where there is little cost beyond factor prices of switching among techniques within a technology (*25*)[2] Using this definition, we associate two technologies with two sets of techniques, and technical change is a switch to or creation of another technology Figure 1 shows our conceptual outline.[3]

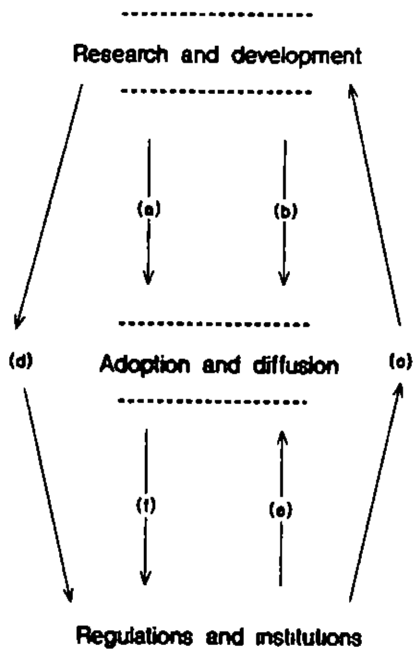
The Three Components

The research and development (R&D) component involves the creation and application of knowledge. This component provides the set of technologies from which firms and consumers choose R&D is usually separated into three stages basic research extends the scientific frontiers of knowledge; product development evolves from applied research, and commercial development focuses on market testing and release

The allocation of R&D funds is a classic portfolio selection problem and, therefore, uncertainty and costs strongly determine the allocation of resources to R&D projects During basic or applied research, technical uncertainty exists about the success of the project Even if a project is technically successful, uncertainty surrounds the possible economic benefits The source of funds for a research program provides an additional source of uncertainty Projects may become impossible to complete within a budget constraint, and research programs that span years or decades can be canceled Costs begin to mushroom as research progresses toward commercial development For example, in plant breeding, the commercial testing of a new variety is twice as expensive as the total cost of all its preceding basic and applied research (*8*)

The adoption and diffusion (A&D) component pertains to firms and consumers who decide to buy new innovations The study of technology adoption focuses on if, when, and why a firm decides to use an alternative or new technology, or a consumer decides to buy a new product (*7, 19*) Several factors affect the decision to adopt an innovation, most notably the performance and relative cost of the innovation, the level of risk aversion, the existence of complementary inputs, and the skill needed to use the innovation The

Figure 1
The process of technical change



study of technology diffusion focuses on the spread of technology over time and can be measured at various degrees of aggregation, such as the farm, county, State, regional, or national levels (*10, 29*)

The regulations and institutions (R&I) component defines the economic, social, legal, and political environment for the R&D and A&D components The institutional setting can both impede and facilitate the process of technical change Harl emphasizes that "one of the significant problems faced by the Third World is the lack of an institutional framework for the development and diffusion of new technologies. . " (*11*, p 112) While the significance of the institutional setting for technical change is often emphasized in a developing country context (*7, 14*), its role in western and centrally planned countries is equally strong. For example, LeBlanc and Hrubovcak attribute about 20 percent of aggregate investment in U.S. agriculture to tax regulations over the period 1956 to 1978 (*18*). The U.S Cooperative Extension Service, created through public policy, brings together farmers, scientists, and government agencies for the transfer and exchange of information on new technology and needs for new technologies

We now turn to the links between the three components of technical change Figure 1's arrows indicate the direction of influence. The three components of technical change are tied together in a dynamic and

[2] More specifically, with inputs x, the jth technique can be written as a production function $F_j(x)$, and a technology T is a set of techniques $T = [F_1(x), \ldots F_J(x)]$ The input requirement set for T is the convex hull of the input requirement sets for the individual techniques (*25*)

[3] Technology continuously evolves over time, and developments in one area can be expected to have spill-over into other areas For the purpose of this article, we focus on technical change in a single area

recursive fashion Due to the recursive nature of these relationships, however, defining a "starting point" for the process of technical change can be difficult Depending on the case, certain relationships are obviously more important, and the following discussion is designed to identify the relevant links for a particular study

The Links Between Components[4]

a The effect of R&D on the A&D component has been studied extensively as the supply-push view of technical change The supply-push view considers technical change to be driven by "autonomous advances in scientific and technical knowledge" (*35*, p 8) Economic forces have no initial influence on the creation of new knowledge Thus, the R&D component provides the set of opportunities among which firms and consumers choose

While it is hazardous to define an advance in scientific knowledge as "autonomous," initial developments in biotechnology seem to offer an example of supply-push In 1973, tools to splice and move DNA pieces between different organisms were discovered (*26*) These tools eventually gave scientists the ability to transfer genes between different species which otherwise would not have been possible As a result, opportunities opened up for understanding and manipulating the physiology and biochemical pathways of organisms

b The demand-pull view of technical change emphasizes how the demands of firms and consumers induce and direct R&D activities which are driven by attempts to take advantage of profitable opportunities The adoption and diffusion of technologies provide new signals to the R&D component about the current and potential market success of an innovation Market success or failure in turn provides incentives to the R&D component to continue or halt further production, marketing, and development. After market introduction, innovations are often further developed and improved, increasing consumer attractability, decreasing average costs, and pushing out of the market other competing firms and products (*1*, *23*, *24*)

Even though general developments in biotechnology gave scientists the ability to create glyphosate-tolerant crops, the perceived opportunity to develop a commercial product directed research toward developing these crops Glyphosate is the largest selling herbicide, accounting for $400 million in annual sales (*17*) Glyphosate-tolerant crops meant the market could expand from the few million acres treated to around 150 million acres (*17*)

Public perception influences the adoption and further development of new technologies [5] Public perceptions, which include safety and environmental concerns like toxic residues in food and social concerns like the protection of rural communities, have been an obstacle for biotechnology R&D For example, some feel that produce from glyphosate-tolerant plants may contain toxic residue Whether or not residues actually exist in the produce, such a perception could alter the adoption and diffusion of glyphosate-tolerant varieties The importance of public perceptions has spawned education and media programs as an integral component of most biotechnology research programs

c. Regulations and institutions clearly affect the ability and incentives to conduct R&D. Regulations are enforced at the Federal, State, and local levels and directly limit or increase the cost to the firm of conducting certain R&D activities The R&I component influences the size and allocation of public research dollars, property rights in new technologies, liability for environmental and human health problems, and market prices.

Agricultural biotechnology regulation provides an excellent example of how the R&I component changes the incentives to conduct R&D The Environmental Protection Agency (EPA), the Food and Drug Administration (FDA), and the U S Department of Agriculture (USDA) are the main agencies that oversee agricultural R&D [6] EPA activities may intersect with FDA activities because chemicals are one form of food contaminant, while all of these agencies have more specialized roles in biotechnology Other Federal agencies in the regulatory process include the National Institutes of Health (NIH) and the Occupational Safety and Health Administration (OSHA)

The indirect costs involved in R&D are substantial For example, firms and research institutions spend time and money to complete tests and apply for

[4]Sub-headings a-f relate to the same letters in fig 1

[5]Smith and others (*33*) showed how lack of consumer confidence (a perception) after a food safety problem significantly affected product demand (Restoring consumer confidence is difficult)

[6]The EPA regulates microbial products, including pesticides, subject to the Federal Insecticide, Fungicide, and Rodenticide Act and the Toxic Substances Control Act (*26*) The FDA regulates the use of food additives, drugs for humans and animals, and food contaminants, and has established different safety levels for each of these areas (*20*) The USDA tests for plant pests, including organisms and products altered, by using genetic engineering under the Plant Pest Act (*26*)

permits to meet regulatory requirements, a process that may not be directly productive from the firm's point of view and can substantially increase the cost of an R&D program Biotechnology managers speculate that they will spend $10-40 million per product to meet regulatory guidelines for new drugs, pesticides, or food additives (*21*, p. 97) Only research institutions or firms that can afford these directly unproductive costs as well as the direct research costs are able to continue to operate Thus, the R&I component can influence the general structure of the R&D industry, including the size and number of firms and entry costs

Regulations that are well defined, clearly established, not redundant, and not in conflict with other regulations reduce uncertainty and facilitate long-term planning. Regulations that do not meet these conditions delay progress, unnecessarily increase the costs of R&D, and may stop some R&D completely According to the Office of Technology Assessment (OTA), "regulatory uncertainty, for example, affects decisions by companies on whether to spend $1-$2 million on greenhouses only because of concern over future field test versus greenhouse work " (*27*, p 211) An added incentive to invest in greenhouse space exists if permits for field testing are difficult and costly to obtain

The cost of time and money of meeting regulatory requirements for glyphosate research has been significant Private companies have been the principal developers, and the EPA is currently the principal regulator of glyphosate-tolerant crop varieties Before the first field test, industry had to apply for testing privileges with the EPA and now must repeat a similar process before testing glyphosate-tolerant crops at a commercial level Until recently, the large amount of paperwork was a disincentive to R&D However, informational requirements in the regulatory process have now become more streamlined (*30*). Such work is not necessarily redundant if new information is acquired during the sequential application process

Like many areas of research, more than one agency will be involved in regulating glyphosate-tolerant crops through to commercial development The FDA may move into this area to test for residue left by a marker gene that accompanies the transferred gene [7,8] Scientists and administrators are worried that FDA requirements may repeat those of the EPA, or may even require returning to a smaller scale of testing To provide a clear and consistent regulatory environment, the EPA, FDA, and USDA have conducted joint reviews of research projects such as a joint regulatory review recently completed for Crops Genetic International

d. The R&D component has a direct and recursive effect on the regulatory and institutional setting in which it is conducted The information and technologies from R&D activities are often associated with new social/moral issues, such as the ability to create transgenic animals, split atoms, clone cells, or mine oceans In response, the R&I component continually evolves to accommodate new opportunities and problems Biotechnology prompted much debate about ethical issues involved in the patenting of new life forms before such patents were initially granted.

Progress in biotechnology, and the uncertainty associated with potentially unwanted side effects, forced Federal and State governments to evaluate, alter, and create regulation for biotechnology R&D Since the government had no prior experience with these technologies, and the uncertainty about their environmental impacts were substantial, regulatory policies were not as coherent as some researchers would have preferred Research scientists demanded and are still demanding a clearer, less costly set of R&D regulations Through such forums as the Transgenic Plant Conference in 1988 and the Federal and State Biotechnology Conference in 1989, government and scientific communities are discussing improvements in regulations

e. The R&I component is naturally tied to the adoption and diffusion of technologies Regulations and institutions define constraints and objective functions that structure the decisionmaking environment and exchange possibilities of firms and consumers. Regulations directly ban or limit certain activities, indirectly affecting others' activities through input prices, output prices, borrowing and lending constraints, and other costs Beyond market incentives, firm and consumer objective functions (profits, utility) are also driven by the social, ethnic, environmental, and cultural background

The effect of government programs, and their relation to technology adoption, is clear in the tobacco industry For example, in March 1989, tobacco growers indicated that they planned to increase plantings by 13 percent over 1988 levels in direct response to an 11-percent increase in the effective quota for flue-cured tobacco, about a 20-percent increase for burley, and

[7]In presentations during the Transgenic Plant Conference, Annapolis, MD, September 7-9, 1988, Stephen Rogers from Monsanto suggested that the FDA may consider testing for possible changes in foods that are produced via genetic engineering

[8]Glyphosate tolerance is achieved through transferring a mutated gene, which is tolerant of glyphosate, from a wild petunia to a tomato plant, with a marker gene, which, if it appears, indicates transformation has occurred

larger allotments for other types of tobacco (*37*) Because tobacco quotas effectively limit acreage planted, the adoption and diffusion of glyphosate-tolerant tobacco varieties can be expected to depend on the prevailing government programs at the time of market release

f The adoption and diffusion of technologies create new environmental, economic, and social conditions that, over time, change the R&I component The adoption and diffusion of new technologies change the structure of agriculture, including location of production, farm size, and numbers of operators This well-known phenomenon is related to the technology treadmill and the evolution toward a larger scale agriculture (*3*)

The recent emergence of biotechnology and its products have caused farmer and consumer groups (the potential adopters) to demand new regulation, both to accelerate the transfer of new technologies to the market and to restrict certain activities Segments of both groups believe that current Federal regulations may result in some unsafe field testing (*22*) These groups feel that the regulatory flaws include confusing definitions of biotechnology, incomplete coverage of research activities, and weak environmental mandates [9]

Consumer groups in California stopped the first field tests of Frost Ban, the biotechnology product that would decrease frost damage (*17*) Due to local worries that the bovine growth hormone (bGH) will be biased toward large farms and accelerate the decline in the family farm, research on bGH may no longer be continued at some land grant universities (*5*) Concern has also been raised about potential side effects of consuming milk produced using bGH technology (*5*), although the FDA has approved the sale of milk for human consumption from FDA-approved research herds treated with bGH (*6*)

Implementing the Conceptual Framework

The conceptual framework is useful if it helps to organize and explain specific cases of technical change An appropriate test of the framework would be to compare the relationships in figure 1 with a group of specific case studies of new technologies (including those that never reached the market) Such an empirical study must wait for research Meantime, this section briefly reviews the development of glyphosate tolerance in tomatoes to summarize the main points of the framework Because glyphosate-tolerant tomatoes are not yet commercially available, we also use the framework to hypothesize about the future importance of certain relationships

Research and development in glyphosate began as a supply-push phenomenon (R&D → A&D), after the first transfer of genes in plants using biotechnology Plant biotechnology initially used crops most amenable to gene transfer techniques and whose genomes (chromosome set) were already well mapped Tomatoes, potatoes, and tobacco fell into this category Thus, general developments in gene transfer techniques, when combined with earlier research on the genome structure of tomatoes, created the necessary technical preconditions for the development of glyphosate-tolerant tomatoes

However, the potential market for new seeds from biotechnology attracted R&D investments toward the area of herbicide tolerance (A&D → R&D) For example, after a survey of 24 firms conducting biotechnology research, Hayenga reported that they typically chose projects with expected markets of more than $10 million per year (*13*) The seed market in general, and glyphosate in particular, meets this requirement The market for glyphosate, the world's largest selling herbicide, could significantly expand with the emergence of glyphosate-tolerant crop varieties

Because of slow growth in the agricultural chemicals market, chemical companies became interested in seed biotechnology (*16*) Through the development of seed varieties tolerant to herbicides, like glyphosate, opportunities arose to create and expand chemical markets

Monsanto, a chemical company, and Calgene, a biotechnology company, are the two developers of glyphosate-tolerant tomatoes Field tests of glyphosate-tolerant tomatoes began in 1987 when Monsanto planted 22 different lines of tomatoes in Illinois These lines tolerated commercial rates of glyphosate application, which is 0 5 to 1 pound per acre (*9*, *31*). Monsanto conducted field tests in Illinois and California in 1988 Calgene held field tests in California during 1988 and 1989 (*36*) Based on current information, glyphosate-tolerant tomatoes are expected to be commercially available by 1993 or 1994 (*31*)

Farmers' perceptions of performance, relative costs, and associated risks, as well as consumer acceptance of the fruit, will affect the adoption and diffusion of

[9]See (*22*) for a detailed discussion

glyphosate-tolerant tomato seeds Potential benefits are lower overall application rates of herbicides, lower herbicide costs, and less crop damage Glyphosate-tolerant plants, however, could carry over as weeds, or could cross with weedy relatives and introduce tolerance into the environment (*2*). While crop management programs can solve such problems, the associated cost diminishes the benefits of adopting glyphosate-tolerant varieties. But, weedy relatives of tomatoes do not grow in the United States, so tomatoes will not likely cross with other plants

We do not know how the adoption of glyphosate-tolerant seeds will affect the use of other herbicides For example, glyphosate could displace other herbicides and require fewer applications. Some argue, however, that the benefits from glyphosate may encourage liberal applications of both glyphosate and other herbicides (*13*, *17*) Until glyphosate-tolerant tomatoes are commercially available, the debate will continue about the possible environmental impacts of the adoption and diffusion of it

Developments in water-quality regulation probably will greatly affect the outcome of this debate (R&I → A&D) For example, water-quality policy may inhibit liberal use of glyphosate through taxing, restricting, or banning certain inputs and practices that pollute ground water The 1990 farm bill, in which water-quality policy is expected to be a major issue, may provide signals about the future direction of environmental policy in the farm sector

Residue from the marker gene for the transferred glyphosate tolerance system could build up in the fruit So, consumer acceptance of the tomatoes from glyphosate-tolerant plants, whether based on perceptions or scientific information, will affect the market price, and, therefore, the revenue side of the farmer's adoption decision [10]

Due to environmental safety and human health concerns raised by consumer, scientific, and environmental groups, Federal regulation has evolved to cover biotechnology activities (A&D → R&I, and R&D → R&I) Because glyphosate is a herbicide, the EPA has jurisdiction over the field testing of glyphosate-tolerant crops Monsanto and Calgene have had to apply for experimental permits from EPA for each field location (R&I → R&D)

The effect of regulatory costs on the incentives to invest in R&D is debated and remains unclear Because the material Monsanto provided for the 1987 and 1988 field tests were almost identical, the regulatory process could create unnecessary costs and act as a disincentive to R&D (R&I → R&D) [11] The current permit process though is designed to access the potential risks of general areas of research as quickly as possible Certain subjects will be identified as relatively safe and will be exempt from permit requirements or have a simplified process Costs of regulation can be expected to decline over time, potential accidents and lawsuits may be avoided, and consumer acceptance of products from biotechnology may increase

The conceptual framework outlined in this paper suggests that the six relationships in figure 1 will influence the direction of technical change Glyphosate tolerance in tomatoes clearly shows that each of these relationships is currently affecting the development of one product from biotechnology The framework also identifies specific issues that must be addressed, such as the relationship between future environmental policy and the incentives to adopt and use new technologies, before the market and social impacts of a new technology can be assessed

Conclusions

The process of technical change is endogenous to the dynamic system within society The framework is simple yet complete enough to detect the main factors that drive technical change The emphasis on the three components of technical change allows the various theories of technical change to be drawn together, more easily related to one another, broadened, and enriched By focusing on the process of technical change, we can understand and direct the path of change toward socially acceptable outcomes

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[10]Consumers have been skeptical of the safety of biotechnology products For example, in an OTA survey, 52 percent believed that biotechnology could be a serious threat to health and the environment (*26*)

[11]Hayenga also reports that the cost of gathering data for a field-test application is $250,000 or more (*13*)

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