BIOTECHNOLOGY AND AGRICULTURE: A SKEPTICAL PERSPECTIVE

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A combination of population and income growth will more than double the demand for food and other agricultural commodities over the next half century. Advances in crop productivity during the twentieth century have largely been based on the application of Mendelian genetics. If farmers are to respond effectively to the demands that will be placed on them over the next half century, research in molecular biology and biotechnology will have to be directed to removing the physiological constraints that are the source of present crop yield ceilings.

Key words: biotechnology; physiological constraints; crop yield ceilings; mendelian revolution

Since the beginning of the industrial revolution, a series of strategic or general purpose technologies have served as the primary vehicles for technical change across broad industrial sectors. In the 19th century the steam engine was the dominant general purpose technology. In the early 20th century the electric generator and the internal combustion engine became pervasive sources of technical change. By the third quarter of the 20th century, the computer and the semiconductor had become pervasive sources of technical change across both the manufacturing and service industries. It is not an exaggeration to suggest that biotechnology is poised to become the most important new general purpose technology of the first half of the 21st century.

A consistent feature of these general purpose technologies has been a long period between their initial emergence and their measurable impact (David, 1990). The steam engine underwent a century of modification and improvement before its widespread adoption in industry and transport. It was half a century from the time electric power was first introduced until it became a measurable source of growth in industrial productivity. Controversy about the impact of computers on productivity continued into the 1990s. It is not yet possible to demonstrate measurable impacts of biotechnology on either human health or agriculture in terms of broad indicators for health (such as infant mortality or life expectancy) or agriculture (such as output per hectare or per worker).

The argument that I make in this paper is that the advances in crop productivity experienced during the 20th century were made possible primarily by the application of the principles of Mendelian genetics to crop improvement. Biotechnology is poised to become an important source of productivity

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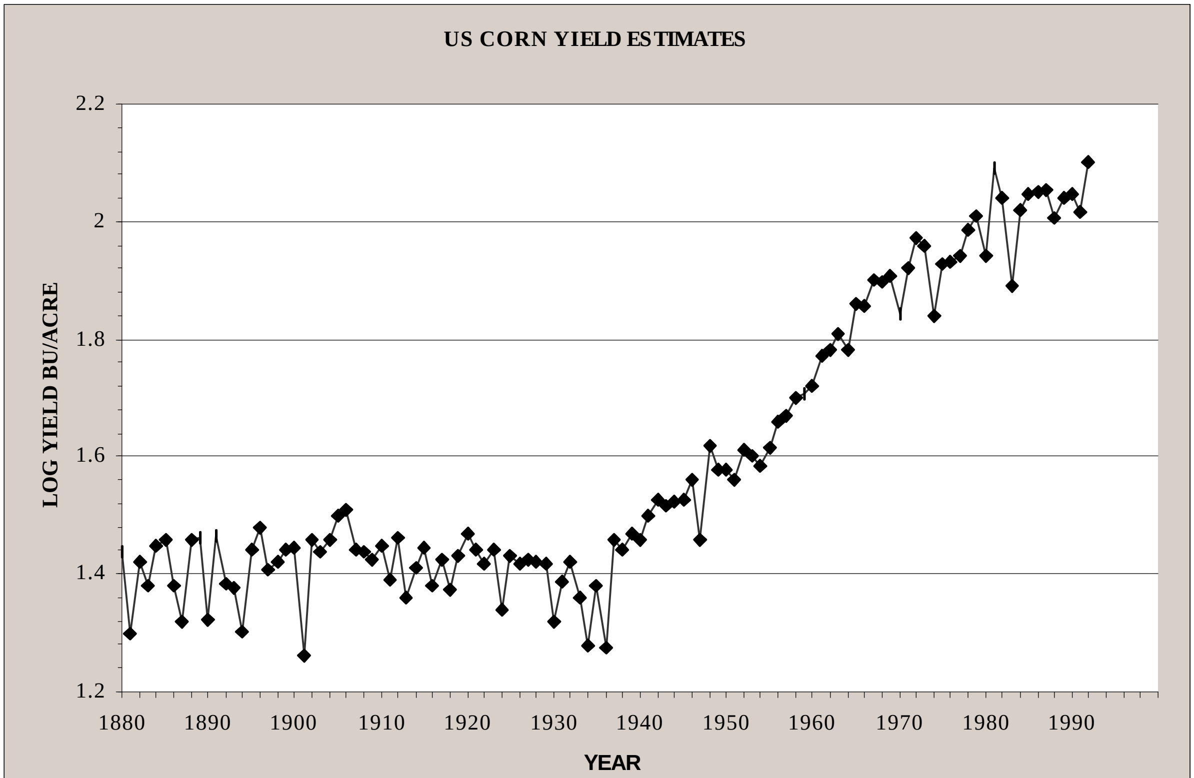
growth in agriculture during the first half of the 20th century. But the advances in the new biotechnology achieved thus far have not yet raised yield ceilings beyond the levels achieved using the older methods. Nor do they promise to do so in the near future.

The Mendelian Revolution

Prior to the beginning of the 20th century almost all increases in crop production were achieved by expanding the area cultivated. Farmer selection had led to the development of landraces suited to particular agroclimatic environments. But grain yields, even in favorable environments, rarely averaged above 2.0 metric tons per hectare (30 bushels per acre). Efforts to improve yields through farmer seed selection and improved cultivation practices had relatively modest impact on yield prior to the application of the principles of Mendelian genetics to crop improvement. In the United States (U.S.), for example, maize yields remained essentially unchanged, at below 30 bushels per acre, until the 1930's (figure 1). It was not until the introduction of hybrids that the corn yield ceiling was broken (Mosher, 1962; Duvick, 1996).



Source: A. Forest Troyer (personal communication, April 26, 1993) Dekalb Plant Genetics

Similar yield increases have occurred in other crops. These increases occurred first in the United States, Western Europe and Japan. Since the early 1970's, dramatic yield increases, heralded as a "green revolution," have occurred in many developing countries, primarily in Asia and Latin America. By the 1990's, several countries in Africa were beginning to experience substantial gains in maize and rice yields (Eicher, 1995).

Yield Constraints

By the early 1990's, however, there was growing concern that yields of a number of important cereal crops, such as maize and rice, might again be approaching yield ceilings. In the Philippines, rice yields in maximum yield trials at the International Rice Research Institute have not risen since the early 1980's (Pingali, 1990). In the U.S., maize yields which had been rising at an arithmetically linear rate of approximately 2.0 bushels per year appeared to be following a logarithmic path (figure 1). Two bushels per year is a much lower percentage rate of increase when maize yield stands at 130 bushels per acre than when it was 30 bushels per acre.

The issue of whether crop yields are approaching a yield plateau has become increasingly controversial. In an exceedingly careful review and assessment of yield trends for 11 crops in the U.S., Reilly and Fuglie (1998, p. 280) found that an arithmetically linear trend model provided the best fit for 5 crops while an exponential model provided the best fit for another five – "but none of the differences between the two models are statistically significant." (Reilly and Fuglie, 1998, p. 280).

Efforts have been made to partition the sources of yield increases among genetic improvements, technical inputs (fertilizer, pesticides, irrigation), and management. I find many of these approaches conceptually flawed.[1] Genetic improvements have been specifically directed to enabling yield response to technical inputs and management. For example, changes in plant architecture such as short stature and more erect leaves have been designed to increase plant populations per unit area and to enhance fertilizer response. The combined effect has been to substantially raise yield per acre or per hectare.

It is hard to escape a conclusion, drawing on the basic crop science literature, that advances in the yields of the major food and feed grains are approaching physiological limits that are not very far above the yields obtained by the better farmers in favorable areas, or at experiment station maximum yield trials (Cassman, 1998; Sinclair, 1998). If present yield ceilings are to be broken, it seems apparent that improvements in photosynthetic efficiency, particularly the capture of solar radiation and reduction of water loss through transpiration, will be required. Even researchers working at the frontiers of plant physiology are not optimistic about the rate of progress that will be realized in enhancing crop metabolism (Cassman, 1998; Mann, 1999; Sinclair, 1998).

The Biotechnology Revolution

The impact of advances in biotechnology on crop yields have come much more slowly than the authors of press releases announcing the biotechnology breakthrough of the week anticipated in the early 1980s. The development of *in vitro* tissue and cell culture techniques, which were occurring in parallel with monoclonal antibody and rDNA (recombinant deoxyribonucleic acid) techniques, would make possible the regeneration of whole plants from a single cell or a small piece of tissue. It was anticipated that the next series of advances would be in plant protection through introduction or manipulation of genes that confer resistance to pests and pathogens. Many leading participants in the development of the new biotechnologies expected that these advances would lead to measurable increases in crop yields by the early 1990's (Sundquist, Menz, & Neumeyer, 1982).

While the early projections were overly enthusiastic, significant applications were beginning to occur by the mid-1990s. The first commercially successful virus resistant crop, a virus resistant tobacco, was introduced in China in the early 1990's. The Calgene Flavr Savr™ tomato, the first genetically altered whole food product to be commercially marketed, was introduced (unsuccessfully) in 1994. Important progress was made in transgenic approaches to the development of herbicide resistance, insect resistance, and pest and pathogen resistance in a number of crops. DNA (deoxyribonucleic acid) marker technology was being employed to locate important chromosomal regions affecting a given trait in order to track and manipulate desirable gene linkages with greater speed and precision. By the 1998 crop year, approximately 70 million acres (28 million hectares) had been planted worldwide to transgenic crops, primarily herbicide or virus resistant soybeans, maize, tobacco and cotton (table 1).

Table 1: Global Area of Transgenic Crops in 1997 and 1998 by Crop and by Trait.

	1997		1998			
Year / Percent	**Millions of Hectares Planted**	**Percentage Area Planted**	**Millions of Hectares Planted**	**Percentage Area Planted**	**Increase (Million Hectares)**	**Factor Increase (1998 / 1997)**
Crop						
Soybean	5.1	46	14.5	52	9.4	2.8
Corn	3.2	30	8.4	30	5.1	2.6
Cotton	1.4	13	2.5	9	1.1	1.8
Canola	1.2	11	2.4	9	1.2	2.0
Potato	<0.1	<1	<0.1	<1	<0.1	N/A
Total	11.0	100	27.8	100	16.8	2.5
Trait						
Herbicide tolerance	6.9	63	19.8	71	12.9	2.9
Insect resistance	4.0	36	7.7	28	3.7	1.9
Insect resistance & Herbicide tolerance	<0.1	<1	0.3	<1	0.2	N/A
Quality Traits	<0.1	<1	<0.1	<1	<0.1	N/A
Total	11.0	100	27.8	100	16.8	2.5

From Global status of transgenic crops in 1998 (ISAAA Briefs No. 8) by C. James, 1998. Ithaca, NY: International Service for the Acquisition of Agri-biotech Applications (ISAAA).

The important point that needs to be made, however, is that the biotechnology products presently on the market are almost entirely designed to enable producers to achieve yields that are closer to present yield ceilings rather than to lift yield ceilings. When I asked the research director of a major commercial seed company when he might expect to see a line in table 1 for higher biological potential his response was "I don't know. There is a lot of hype out there." One reason for the cautious response is that attention is shifting away from yield to a second generation emphasis on quality traits.

More Generations

Even as we move into the initial years of the first generation of agricultural biotechnologies, second and third generation technologies are being enthusiastically heralded (Kishore, 1998). The objective of the second generation, now being explored at the laboratory level, is to create value downstream from production. DuPont recently introduced a high oil maize which, though not strictly a biotechnology product, is often referred to as an example. Efforts are being directed to develop cereals fortified with the critical essential amino acids such as lysine, methionine, threonine, and tryptophan for use in animal feed rations and in consumer products. It is also anticipated that oilseeds will be modified to enhance their content of trans-fatty acid free fat and protein quality (Kalaitzandonakes & Maltsbarger, 1998).

A third generation of biotechnologies, directed to the development of plants as nutrient factories to supply food, feed and fiber, is also anticipated. High carotene fruits, vegetables and oils designed to reduce Vitamin A deficiency, is one example. In the longer run it is anticipated that biotechnology will revolutionize crop production and utilization technology. Processed feed and food will be grown in fermentation vats using biotechnology engineered micro-organisms and generic biomass feedstocks (Rogoff & Rawlins, 1987; J. Reilly, personal communication, January 25, 1999).

In a fit of what can only be characterized as "irrational exuberance" some biotechnology publicists have proclaimed that the benefits of new value-added grain production systems will be shared equitably among producers, the biotechnology and food industries, and consumers. In addition, these systems will eliminate the historic cycles of price and profit instability associated with traditional commodity market instability (Freiberg, 1998). It is not too difficult to hear echoes of the hype of the early 1980s when the first generation biotechnologies were still in the laboratory.

Some Concerns

I am concerned that more intensive research efforts are not being devoted to attempts to break the physiological constraints that will limit future increases in crop yields. These constraints will impinge most severely on yield gains in those areas that have already achieved the highest yields. It is possible that advances in fundamental knowledge in areas such as functional genomics, for example, might provide a scientific foundation for a new round of rapid yield increases. This would, in turn, enhance the profitability of private sector allocation of research resources to yield improvement. But it would appear exceedingly rash to predict that these advances will leave any measurable impact on production within the next several decades (Duvick, 1996).

I am concerned that many developing countries have not yet acquired the research and development capacity necessary to enable their farmers to realize the potential yield gains from crop improvement efforts. In most developing countries, yields are still so far below existing biological ceilings that substantial gains can be realized from a strategy emphasizing traditional crop breeding combined with higher levels of technical inputs, better soil and crop management, and first generation biotechnology crop protection technology. Since the fastest rates of growth in demand, arising out of population and income growth, will occur in the poorest countries, it is doubly important that they acquire the capacity to sustain substantial agricultural research efforts.

I am also concerned about the economic and scientific viability of public sector agriculturally oriented research in developed countries. Since 1980, the resources available to the federal government (U.S. Department of Agriculture) agricultural research system has remained essentially unchanged in real terms. Public support for the state agricultural experiment stations (from federal and state sources) has barely kept up with inflation.[2] The economic viability of private sector research requires that it be directed to the development of proprietary products. It is important, for the scientific and technical viability of private sector agricultural research, that the capacity of public sector institutions to conduct basic and generic research be not only maintained but enhanced.

Endnotes

[1] In the mid-1990s, Donald N. Duvick (1997) of Pioneer Hybrid International conducted a series of very careful experiments to determine the relative contribution of increases in maize yields due to breeding. His results suggest that plant breeding contributed about 60 percent of the yield increases between 1935 and 1975. Donald N. Duvick has also suggested in correspondence (personal communication, February 13, 1999) that by the mid-1990s in the U.S. and other developed countries, the relative contribution of plant breeding is probably higher than in the period he studied because there are fewer increments to yield being realized from more effective weed control or higher levels of nitrogen fertilizer application. Duvick also reminded me that advances in crop yield from plant breeding has been due at least as much to the tacit knowledge of experienced breeders as from the application of the principles of Mendelian genetics.

[2]The Department of Plant and Microbial Biology at the University of California-Berkeley has recently entered into an arrangement to sell its "research product" to Novartis (Wein, 1999). A number of similar relationships had been developed between private universities (Harvard, Massachusetts Institute of Technology, and Washington University) and large pharmaceutical companies in the early 1980's. The Berkeley arrangement is controversial, primarily because it is the first time a major public university has entered into such a close arrangement.

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