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BIO ECONOMIC RESEARCH ASSOCIATES

Agricultural Biotechnology at the Crossroads

PART I: THE CHANGING STRUCTURE OF THE INDUSTRY

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Executive Summary

The structure of the agricultural biotechnology industry is evolving rapidly in response to competitive pressures and the high costs and risks of developing new products. Integrated agrochemical and seed companies have been the driving force for research and development in recent years, accounting for the majority of R&D output measures. These companies have the research capabilities, financial strength, and complementary intellectual property assets to support product development cycles that span 6–12 years.

Based on research and development efforts over the past decade, biotechnology companies are now moving toward commercialization of hundreds of new plant varieties—including second-generation crop protection traits, biopharmaceuticals, and biomaterials. Yet political and institutional opposition to genetically modified organisms remains strong in some markets, especially in Europe. Accordingly, companies in this sector are being forced to develop new strategies for engaging and influencing other stakeholders.

CONTENTS

Bio Economic Research Associates (bio-era™) is a leading provider of independent research and advisory services regarding the bio economy. Our primary mission is to help decision-makers understand and respond to the economic and societal impacts of human-induced change to biological systems. We provide independent and objective strategic insight, perspective, and knowledge.

Our research and advisory services provide independent, authoritative bio-era research as well as access to our network of specialists. Our client relationships are highly interactive, and include opportunities for participation in bio-era conferences, scenario workshops, learning journeys, and other events that bring together diverse stakeholder groups with bio-era experts.

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This report is the first in a series of publications from bio-era's research project, *Agricultural Biotechnology at the Crossroads*, which will describe and assess the institutional and economic landscape of agricultural biotechnology. The report series will identify the major stakeholder groups whose interests converge and sometimes collide around the uses of biotechnology in agriculture. This includes, among others, the companies directly involved in agricultural biotechnology, non-governmental organizations with agendas related to this industry, the food industry, and the farm sector. The first two reports in the series are described here.

Part I: The Changing Structure of the Industry examines the evolving structure of the agricultural biotechnology industry itself. Which companies are active in this market? How is the structure of this industry changing? What are the driving forces that are shaping the economic future of the industry? What new technologies are emerging that will have significant consequences for the industry?

Part II: Advocates and Analysts will focus on not-for-profit stakeholder groups and interests, including non-profit conservation groups, environmental and public health advocacy organizations, industry and trade associations, and allied university research centers and interests. What interests do these various groups have? What are their constituencies and sources of their funding? What roles do they play?

These reports, together with other materials and research reports addressing a wide range of issues affecting the bio economy, will be used to provide context and support for bio-era's forthcoming scenario planning project, “Biology & Borders: The Future of the Global Bio Economy.”

Introduction

Agricultural biotechnology occupies a central position in the bio economy. The impacts of biotechnology—including fundamental innovations in products and processes, shifts in consumer attitudes, regulatory conflicts and change, and industry restructuring—far outweigh the relatively small proportion of revenues accounted for by companies developing and marketing these new technologies in agriculture.

Having emerged as a major force in global food production over the past decade, the future of this new industry is now enmeshed in controversy surrounding an extremely complex set of economic and environmental questions. To survive and prosper, companies in this sector are being forced to develop more sophisticated and nuanced strategies, reflecting a deeper understanding and integration of the interests and perspectives of other stakeholders with the power to influence consumer choice, politics, regulation, and trade.

Environmental Challenges

Concerns about the potential environmental and health risks associated with genetically modified plants and animals (GMO's) have served as a brake on the advance of biotechnological applications, especially in Europe[1]. Objections raised against the deployment of these organisms include concerns that their introduction could:

- disrupt natural plant and animal ecosystems
- pollute other plant species and non-GMO crops through unintended gene flow
- compromise natural plant defenses or immune responses
- accelerate the evolution of resistance on the part of crop pests
- introduce new allergens into human food supplies, or
- contaminate food crops with biologically-active pharmaceuticals or other products.

But GMO's also hold tremendous promise for solving many environmental, nutritional, and food security problems, most notably by offering alternatives to chemical pesticide application, reducing tillage, improving nutritional value, increasing yields, and adapting crops to climate change.

Economic Challenges

The key economic issues facing the agricultural industry as a result of genetically engineered crops and production systems include the impact of uncertain consumer adoption, midstream storage, processing, and transport of GMO's, the reallocation of value within the food production value chain, and international shifts in competitive advantage and trade flows. Moreover, the introduction of genetically modified organisms presents a completely new and potentially profound set of financial risks and liabilities for seed companies, farmers, food processors, and others because of the potential for cross-contamination of crops through cross-pollination, regrowth of volunteers from previous plantings, and after-harvest handling. Finally, many

What is the bio economy?

We define the bio economy as including all industries, economic activities, and interests organized around living systems. We see the bio economy as divisible into two primary industry segments: (1) the bioresource industries, that directly manage or exploit biological resources: crop production, livestock and poultry, aquaculture, forestry, fishing and horticulture, and (2) the related industries that have large stakes as either suppliers or customers to the bioresource sector: agricultural chemicals and seeds, biotechnology and life sciences, energy, food and fiber processing and retailing, banking, insurance, pharmaceuticals and healthcare. All these industries have a vital interest in the economic impact of human-induced change to biological systems.

analysts see the economic impact of the first generation of bioengineered crops, which have largely focused on crop protection, as exerting further downward pressure on prices for these crops, leaving relatively little gain for producers.

A Clash of Values

The scope of these issues should come as no surprise. The biotechnological revolution that promises to transform the world economy over the next century is a cultural phenomenon of deep significance in human history. Recent developments in genomics and biotechnology crystallize longstanding conflicts over our relationships to technology and to the natural world. Brian Arthur, an economist with the Santa Fe Institute, has suggested that public attitudes about biotechnology, which are often highly emotional, reflect an underlying collision between two deeply held, yet contradictory views[2]. On the one hand, industrialized societies tend to put great hope in technology, with the expectation that technological progress will solve a wide range of problems and improve the quality of our lives. On the other hand, people instinctively trust nature in ways that can supercede their hopes for technology. The "Frankenfoods" label coined by environmentalists against genetically modified foods invokes imagery that exploits this deep underlying conflict in values.

The industry is poised,technologically, to unleash a dizzying array of genetic innovations in the years ahead, supported by rapid advances in basic science and genetic engineering tools.

The Crossroads

The biotechnology industry today stands at a crossroads. The industry is poised, technologically, to unleash a dizzying array of genetic innovations in the years ahead, supported by rapid advances in basic science and genetic engineering tools. These innovations present a broad palette of new applications, including not only new crop protection measures, but also improved food quality and nutritional value, non-polluting processes for producing plastics and other organic chemicals, new sources of biologically produced energy, less-expensive production methods for pharmaceuticals, and bioremediation for environmental clean-up.

In direct contradiction to this growing potential for new and transformative product innovations, indications are that, at least in the short run, biotechnology companies will face still higher hurdles in introducing new genetically engineered products. Recent developments signal the challenges that lie ahead:

- In February, 2003, an influential industrial working group in Canada, comprised of representatives from the Canadian Wheat Board, farmers, millers, elevator operators, and other organizations proposed a rigorous set of guidelines for evaluating potential costs and benefits before allowing the introduction of genetically modified wheat in Canada. The group specifically called for consideration of the potential impacts of losses of international markets in evaluating the introduction of new varieties of wheat. If accepted, the proposed "regulatory market impact test" would mark a departure from the "science-based" criteria used previously and could significantly slow or even permanently block the introduction of genetically modified wheat varieties. In its communiqué, the group stated that "forsaking the wheat industry for pro-biotechnology goals or free trade ideals is unacceptable."[3]

- Ten U.S. food industry groups, including the Grocery Manufacturers of America, the Food Marketing Institute, and the National Restaurant Association urged the government to halt the growing of "bio-pharm" crops until stricter regulations can be put in place to prevent accidental contamination of other crops.

- New regulations under the U.S. National Organic Standard Program, which became effective in 2002, will impose limits on genetically modified products in certified organic foods. The U.S. market for organic foods now exceeds $10 billion and has grown at approximately 20 percent per year in recent years.

- Public opposition to genetically modified foods in Europe appears to be hardening, and governments are responding with entrenched support for labeling of food products containing genetically modified ingredients. Products that contain more than 0.9 percent EU-approved genetically modified material will have to be labeled.

While consumer tastes, attitudes, and buying patterns are subject to change, the market environment for agricultural biotechnology, at least in the near term, is less than completely friendly. Neil Harl, professor of economics at Iowa State University writes: "In the types of open, transparent, market-oriented economic systems which now dominate the world, the consumer, through the exercise of consumer choice, provides a continuing plebiscite over every feature of food supply. The consumer may be right or wrong, informed or misguided, flippant or serious-minded. Nonetheless, it is consumer choice that drives the entire food system."[4]

Notwithstanding these serious challenges, we believe that the biotechnology industry has the potential to bring to market new agricultural products with highly attractive economic and environmental attributes. The following examples are indicative of these opportunities:

- Crop protection traits may significantly increase yields for farmers in parts of the world where pest pressures are high and chemical pesticides are prohibitively expensive. A recent study demonstrated 80 percent higher yields for Bt cotton crops in India when compared with traditional crop varieties in field trials.[5]

- If concerns about contamination of food supplies can be overcome, plant-based plastics, polymers, and films may begin to make inroads into a $60 billion dollar U.S. market now dominated by petrochemical companies.

- Other biotech crop-derived products could include lubricants and functional fluids, inks, enzymes, and renewable synthetic fibers and packaging with advanced properties.

- Many new genetically modified crops are poised to improve the nutritional or quality attributes of food products including the removal of allergens, as in peanuts.

- Plant-based pharmaceuticals could present a multi-billion dollar market opportunity. Epicyte Pharmaceuticals believes its plant-based process can make the same annual quantity of drugs with 200 acres of corn that a $400 million factory would produce in an animal-based system.

To capitalize on the potential opportunities that lie ahead, we believe the biotechnology industry will need to break the current impasse by directly engaging opposing stakeholders in trust-building, collaborative, mutually educational processes. This will require that companies in the biotechnology industry, individually and collectively, enhance their capabilities to effectively advocate for market acceptance of their products. We believe this kind of advocacy, or social marketing, will become a critical core competency of successful companies, complementing their intellectual property assets, research and development capabilities, and conventional marketing strength.

Companies using biotechnology must strengthen their abilities to work with other stakeholders

To achieve this, companies using biotechnology must first strengthen their capabilities to work effectively with the many stakeholders whose interests are affected by their bioengineered products. This includes farmers, food processors, consumer environmental groups as well as university and other public-sector research programs which hold significant intellectual property assets and may be influential allies in evaluating risks and making the case for the benefits of genetically engineered products. In other industries, notably the electric utility sector, collaborative work with environmental advocacy organizations has successfully circumvented more costly regulatory and legal battles. To achieve such collaboration, biotechnology companies will need to demonstrate leadership in addressing ecological and evolutionary dimensions of biotechnological applications.

Second, companies will need to communicate and advocate effectively, in order to influence public opinion and political decision-makers in key markets worldwide. Companies in other technology-dominated industries like pharmaceuticals, telecommunications, and energy have long invested in regulatory advocacy and public relations, with widely varying degrees of success. In agricultural biotechnology, U.S. actions to overcome European restrictions on genetically modified foods will only be effective if they are complemented by effective measures to inform and make amends with the European consumer.

Third, major companies will need to carefully manage their brand identities in order to build trust on the part of consumers and regulators. The "New Monsanto Pledge" adopted by that company several years ago is an example of the kind of steps that need to be taken in this direction.

Altogether, we believe these changes mean that new product introductions today and in the years ahead will be marked by a set of characteristics quite different from those in the initial phase of the industry's development, as illustrated in Table 1.

Table1. Introducing Biotech Products: a new phase for the agricultural biotechnology industry

Initial Phase (1996-2002)	Current Phase (beginning in 2003)
Crop-production orientation: single trait crop protection	Broader emphasis on consumer-oriented food quality and nutritional attributes, biomaterials, and pharmaceuticals; multiple, stacked traits for crop protection
Focus on corn, soybeans, cotton, and canola	Additional focus on potato, tomato, rice, tobacco, and other crops
Rapid market deployment	Staged deployment according to predetermined milestones
Ready farm acceptance	Cautious acceptance in new crop markets; suppliers work closely with farm sector stakeholders
Limited enforcement of GM crop segregation	New procedures for GM crop testing and segregation in production, transportation, and processing are possible

Market Performance

Agriculture is only one among a variety of industries in which the rapidly developing tools of biotechnology are finding applications. Overall, the biotechnology services industry includes a large number of research and development service firms specializing in serving the needs of different downstream industries. Of the over 1,200 identified "biotechnology" companies in the U.S., only about 10 percent specialize in plant or animal agriculture.[6] The lion's share of biotech firms, over 55 percent, focus primarily on human healthcare. Yet agricultural biotechnology is being developed and applied by more than just biotech R&D service firms. University and government research laboratories contribute an enormous amount of financial and human resources toward advancing both biotechnological and agricultural research. Established firms in the agricultural industry are the primary conduits through which biotechnological products make their way to market, and the single most important conduit is commercial seed sales.

Global commercial seed sales in 2001 were $16.7 billion; of this, 18% or $3.0 billion were genetically modified seeds.[7] Just three major crops—corn (maize), cotton, and soybean—made up 95% of the total genetically modified crops grown in 2001.[8] Given estimates of the contribution of the seed component and the additional genetic trait component to gross margins in these three crops,[9] we estimate that the gross margin from added genetic traits in the global seed market was about 22% of genetically modified seed sales, or $673 million, in 2001.

While sales of genetically modified seeds are increasing (13% between 2000 and 2001), sales of conventional seeds are stagnant or decreasing, and sales of crop protection chemicals are decreasing. The decrease in chemical sales in 2001 resulted from a number of factors, including weather and grain prices, but was also in part due to substitution by crop protection seed traits.

There are two factors that significantly influence projections of future market size and potential in agricultural biotechnology. The first is the potential for introducing new agricultural product streams—including nutritionally enhanced foods, biomaterials, bioenergy, and biopharmaceuticals—some of which serve industries in which commodity agricultural producers do not currently compete. The second is the anticipated changes in market structure that these introductions may bring to the vertical alignment of agricultural value chains. We believe concerns about product containment for commodities with value added and highly differentiated biomolecules will eventually be addressed through arrangements analogous to those now seen in the poultry sector, where providers of genetics contract with independent growers under specific terms for containment and handling. Thus, as new opportunities for agriculture are opened up by biotechnology, their value will be reflected in new ways, beyond seed and agrochemical sales.

The primary market for genetic inputs to the agricultural industry is commercial seed sales.

Forces Shaping the Outlook for Biotechnology

We believe that the future of agricultural biotechnology will be shaped by several major "driving forces" (see Table 2). These are the long term, underlying forces for change in the industry.

Enabling technologies. The extraordinary ongoing advances in genomic, proteomic, and metabolomic tools and technologies represent an irrepressible force for change, as they continue to make gene discovery and genetic transformation cheaper and faster by orders of magnitude compared with technologies available just a few years ago. Our technological capabilities to sequence DNA or synthesize it from scratch are improving at rates faster than Moore's Law.[10] These advances are opening the doors to extensive new applications of genetic engineering, as described later in this report.

Complementary intellectual assets. To take advantage of new technological opportunities for directly tailoring the genetic makeup of crops, firms must have access to a triad of specialized capacities, including enabling technologies for plant genetic transformation, trait-conferring genes, and elite crop germplasm, all three of which have been patentable in the U.S. and other major markets since the 1980s. These three types of intellectual assets are mutually complementary: more of one yields an increase in the marginal value derived from the other two. These complementarities generate incentives for firms to gain access to all three. However, for a variety of reasons, firms confront serious difficulties and transaction costs in accessing these assets from external sources via licensing agreements. One response has been the aggregation of intellectual assets through acquisitions and mergers.[11]

Some evidence suggests that the advent of RoundUp Ready corn and soybeans has intensified selection pressure and accelerated the evolution of weeds resistant to glyphosate.

Other responses that will emerge as the technology space expands and matures include more sophisticated arms-length licensing transactions and R&D alliances. The public sector is exploring a collaborative IP license clearinghouse to solve complementary asset coordination problems for specialty crops and humanitarian aid projects.[12]

Evolution of resistance. The ability of weeds and insect pests to evolve resistance to crop protection measures has far-reaching implications for commercial strategies in agricultural biotechnology. Already, the evolution of resistance by crop pests poses a challenge to the long term use of some of the world's most widely grown genetically engineered crops after only five years of widespread use. Over 250 herbicide-resistant weed biotypes have been identified worldwide, across a broad spectrum of different types of herbicides.[13] Similarly, the track record for insect pests evolving resistance to pesticides is a long and impressive one.

Ironically, commercial success in gaining large market share for genetically engineered crop protection measures may accelerate the evolution of pest resistance and thus undermine the value of the product over time. Some evidence suggests that the advent of RoundUp Ready corn and soybeans has intensified selection pressure and accelerated the evolution of weeds resistant to glyphosate (the active ingredient in RoundUp), since RoundUp is now used year after year despite corn and soybean rotations. Similarly, recent studies have shown that insect pests that feed on Bt corn in the summer fly south to infest Bt cotton crops in the fall.[14] The use of Bt toxin in both crops increases selection pressure for the evolution of resistance.

The evolution of resistance, therefore, sets the clock running on the value of intellectual property assets in the area of crop protection. A variety of strategies have already emerged to protect and extend the value of investments in these assets by attempting to manage the evolution of resistance after the fact. Examples include attempts to regulate or stipulate farm practices, and the engineering of additional protections into later generations of these products (trait stacking). However, perhaps the greatest opportunity for improvement in this area is to apply our rapidly growing knowledge of co-evolutionary system dynamics during the design stage of product development. We believe applied evolutionary and ecological theory can help the industry minimize or avoid these kinds of problems in the future.

Conflicting regulatory environments. Key decisions about the future of agricultural biotechnology will be made in the halls of regulatory agencies in Europe and the major developing countries like China, India, Indonesia, and Brazil. Japanese regulations will have some sway on Asian exporters, but suppliers to Japan have long given exports to Japan special treatment to meet demanding quality regulations and market tastes. The specter of lost exports to Europe, however, has stalled adoption of these technologies in many markets around the world. Entrenchment of strict regulatory requirements in Europe could lead the major firms to abandon European markets altogether, and could create two agricultural commodity trading blocs in the world, one centered on trade with America and following its relatively liberal regulations, and the other centered on Europe (and to a lesser extent Japan) and their technological conservatism.

Two forces drive the conservative regulatory stance. First, European regulatory agencies are more diffuse, split between national governments and the EU, and have endured a series of major recent regulatory crises, including those related to the spread of mad cow disease, hoof and mouth disease, and the discovery of dioxin-infested chickens in Belgium. These factors may contribute to efforts to pass much of the responsibility for accepting and adopting these new technologies directly on to the consumer, by requiring labeling about genetic technologies on product packages and then allowing consumers to "vote with their pocketbooks" based on that information. Second, European firms have had less incentive to pressure European regulators to clear the way for adoption of these technologies in European markets. European firms have, in general, lagged behind their American counterparts in both developing innovative new biotechnology products and in bringing new genetically modified seed to market. At the same time, leading European firms have larger market shares in agricultural chemicals exposed to competitive displacement by new biotechnologies. Because the current European regulatory environment discourages patents on classes of technologies in which European firms are less competitive and severely restricts the planting of the genetically modified seeds that have shifted agrochemical market shares elsewhere in the world, the recent allegations of protectionism by the U.S. are not surprising or unexpected. Whether U.S. threats to file a trade complaint at the WTO are also wise in light of the consumer challenges facing the agricultural biotechnology industry is debatable.

Gene escape, genetic pollution, and trait recombination. Unintended of gene flows from genetically modified crops to non-genetically modified crops, weeds, and other species could create problems in the farm economy and present environmental concerns. Problems resulting from contamination of organic or non-genetically modified crops could lead regulators to impose stricter requirements for maintaining buffer zones around certain crops, or even impose liability on producers whose crops contaminate neighboring crops.

Value differentiation in food and agriculture. Trends toward greater product differentiation in rich countries, include GMO/non-GMO, organic, and multiple layers of quality and nutritional attributes. DNA "bar coding" has been proposed to provide simple ways of identifying GM foods. As in other industries, this may open up new value creation opportunities.

The evolution of resistance, therefore, sets the clock running on the value of intellectual property assets in the area of crop protection.

Table 2. Driving Forces Shaping the Future of Agricultural Biotechnology

Driving Force	Indicators/Characteristics	Strategic Responses	Implications for Value Chains
Advances in genomic, proteomic and metabolomic tools and transformation technologies	Cost and time for gene discovery and genetic transformations continue to fall steeply Genetic engineering capabilities expand exponentially	Rapid advances in applications of plant biotech to biomaterials, pharmaceuticals, bioremediation, and bioenergy products Acceleration of consumer-oriented food quality and nutritional development	New, less-constrained avenues for value creation beyond traditional agricultural commodities will emerge
Complementarities among intellectual assets	Patentable intellectual assets including tools for plant genetic transformation, genes, and elite crop germplasm are highly complementary Transactions costs are high for accessing these assets from external sources via licensing agreements	Consolidation of balanced portfolios of intellectual assets through mergers and acquisitions Innovative intellectual property (IP) licensing practices Public sector IP clearinghouses to reduce transactions costs	A small number of elite companies that dominate seed and chemical markets for major crops will be able to price strategically Holders of IP assets will harvest returns available from GMO applications; competition in farm sector will erode benefits
Evolution of resistance	Pests evolve resistance to crop protection measures Increased market share for a given crop protection measure may accelerate the evolution of resistance	Management of resistance through contractual and regulatory requirements Succession planning and diversification of crop protection portfolios to provide integrated solutions	Value of IP assets and product lifecycles influenced by management of resistance Returns to farmers and farm land values may be reduced because of the evolution of resistance
Consumer and corporate resistance to GM crops resulting in conflicting regulatory environments	US and EU divisions over regulation of GM foods solidify Possible market segmentation into trading blocks according to GM food standards	US government actions within WTO to challenge restrictions on GM foods Biotech industry focus on new products with consumer/health-oriented attributes	Non-GM crops may sustain modest price premiums; permanent loss of some export markets for GM crops Civil liability issues multiply throughout food value chains Increased farm sector resistance to new GM crops in some areas New government regulations based on gene-flow concerns could limit markets for GM crops
Gene escape, genetic pollution, and trait recombination	Gene flows from GM crops to non-GM crops, weeds, and other species Unintended combination of traits introduced by GM crops	Requirements for buffer zones surrounding GM crops Engineering of crops to reduce the likelihood of gene flows	Gene ownership, liability and patent rights may be affected by accidental movement of genes among species or crop varieties
Value differentiation in food and agriculture	Greater product differentiation More labeling of products	New business opportunities in technologies for labeling, identification, and segregation throughout supply chain Opportunities for premium biotech products	Greater price differentiation in wide range of agricultural products

Changing Industry Structure

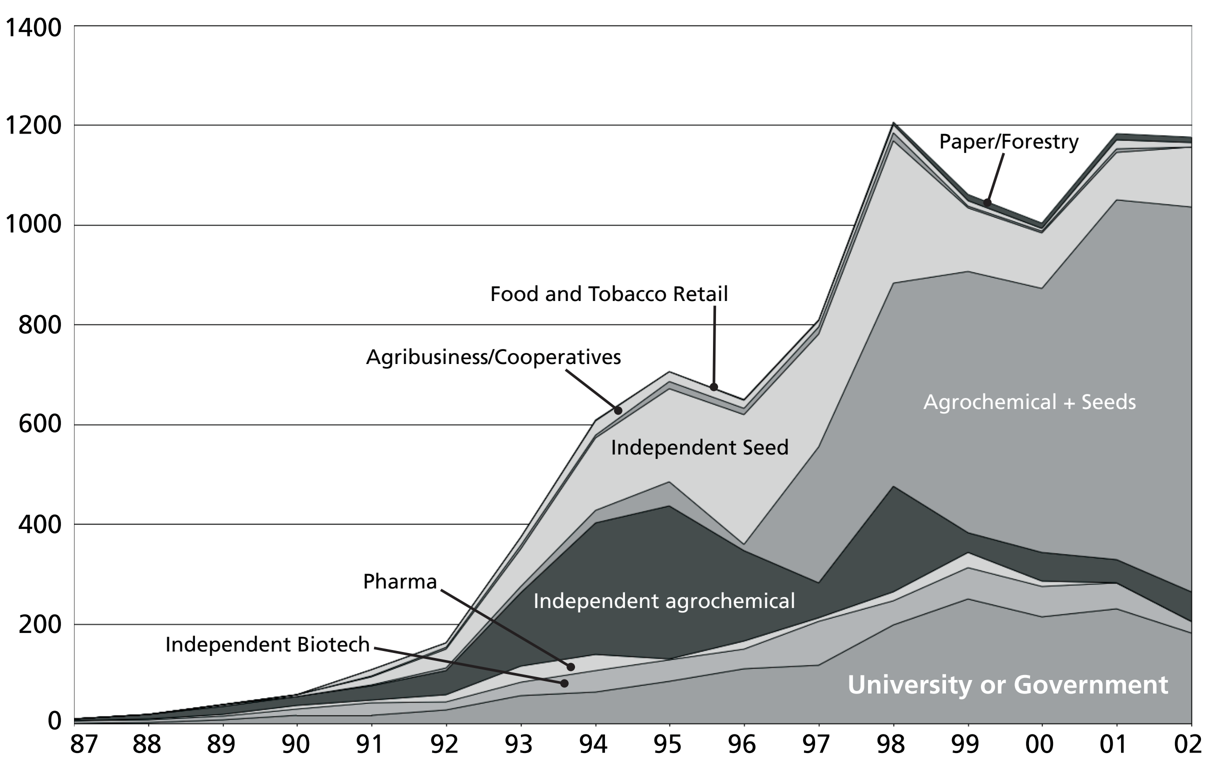
The agricultural biotechnology industry has been transformed in recent years by a major wave of restructuring and consolidation. A few large agro-chemical companies now account for most of the industry's activity in the commercialization of genetically modified crops, as well as much of the research and development leading to new products.

The share of research and development activity accounted for by independent seed companies—those without ties to chemical companies—has declined significantly since 1998 as these companies have been acquired by chemicals companies. The agrochemical companies are strategically positioned to take advantage of the complementarities between chemical and biotechnological products, and are likely to be strongly positioned relative to firms producing either of these products separately. Combined seed and chemicals companies are able to price their products strategically to take advantage of these complementarities.[15] These pricing decisions will, in turn, have important implications for the distribution of economic benefits derived from genetically modified crops.

Universities account for the second largest share of research and development activity in the industry. In the United States, for example, universities accounted for 19% of all field trials of genetically modified organisms conducted between 1997 and 2002. The role of universities is especially significant in terms of the support it provides for research and development of plant varieties for markets in which the large multinational firms have little interest. Many of these development activities are tied to local interests: the University of Georgia conducts research on peanuts; Texas A&M, grapefruit; Oregon State, poplar trees; Louisiana State, rice; and the University of North Carolina, tobacco. Recent economic studies have confirmed a strong positive correlation between the number of universities that are active in the research and development race and the number of commodities to which the innovation is applied.[16]

Universities account for the second largest share of research and development activity in the industry.

Figure 1. The evolution of the agricultural biotechnology industry, based on numbers of US field trials of genetically modified organisms.



The complex evolution of relations among the agrochemical, seed, and biotech sectors must be understood in order to grasp the nature of the business today.

Agribusiness firms handling and processing farm output, such as Cargill, ConAgra, and Simplot are strategically positioned to capture value added by quality enhancements, biomaterials, and other output traits. These firms have until now only been peripherally involved in biotechnology but are beginning to seek major inroads by striking alliances with the dominant agrochemical companies. Cargill and Monsanto have a joint venture, Renessen, and Bunge and Du Pont recently announced an intended joint venture named Solae for joint development and commercialization of value added commodities.

Figure 1 illustrates the evolution of the agricultural biotechnology industry measured by the numbers of field trials of genetically modified organisms[17] conducted in the United States in each sector since the industry's inception. From the late 1980s until 1996, the industry's structure was fairly stable. Agrochemical and seed firms were the most active sectors in the early years, largely as separate lines of business. Publicly funded agricultural research and development at universities and government labs held the third largest share, followed by independent biotechnology firms. On the fringes, a few pharmaceutical, food, and tobacco firms also tried their hands at genetically engineering organisms for applications in agriculture.

Today, after fifteen years of industry evolution, the great majority of field trials are undertaken by agrochemical businesses that have merged with complementary seeds businesses. These firms include Monsanto, Dow AgroSciences, Du Pont-Pioneer, and Syngenta. The public sector has continued to grow at a modest rate, although the numbers of trials conducted by universities has declined slightly since 1999. Industry consolidation has significantly drawn down the numbers of independent agrochemical and seed firms still active in agricultural biotechnology. Independent seed firms, mostly smaller firms developing varieties with traits licensed from the large agrochemical firms, rank third among the categories of organizations conducting field trials. Some major agrochemical firms, such as BASF, Sumitomo, and FMC, still have little or no appreciable seed business in house. Significantly, the magnitude of involvement from independent biotech firms has remained stable over time in absolute terms, but has not grown with the industry. Today, most independent biotech firms involved in the sector are providing upstream research and development services in genomics and bioinformatics for the major integrated agrochemical firms, leaving the applied work of product development and field testing to the majors. Fringe involvement is still seen from food and tobacco firms as well as forestry and paper product firms. Pharmaceutical firms have all but left the industry.

The economic interests of the eight sectors illustrated in Figure 1 differ significantly. In particular the complex evolution of relations among the agrochemical, seed, and biotech sectors must be understood in order to grasp the nature of the business today and to see the possibilities for its future. We examine each sector briefly in turn, beginning with the most dominant sectors:

1. Agrochemicals. Most of today's integrated agrochemical firms began their ventures into biotechnology in the late 1980s and early 1990s under "life sciences" strategies; and most of these firms had a relationship of some sort with a pharmaceuticals business.[18] The first major round of consolidations reached its peak in 1996-97 as large agrochemical companies increased positions in genetic engineering and gene trait technologies by acquiring leading independent plant biotech firms.[19] They also sought germplasm rights and access to seed markets by integrating major commercial seed firms.[20] The latest phase of evolution in the agricultural biotechnology industry has been the divorce of agriculture from pharmaceuticals, marking the demise of the life sciences strategy. Newfound independence in some cases drove further consolidation of the now integrated agrochemicals-seed firms in a second, smaller round of consolidation in 2000-01.[21] Interestingly, both rounds of consolidation correspond to sizable dips in industry-wide field trial activity.

For each agrochemical firm there have been moments of truth in deciding whether or not to continue to invest heavily in biotechnology. In the U.S., these decisions appear to have been influenced significantly by the rising costs to the companies of increasingly stringent regulations governing the development of chemical pesticides. However, the magnitude of investments required to succeed with bio-based strategies is substantial and this has driven smaller and less diversified chemical firms away from biotechnology.

Table 3.
Top agrochemical producers by global sales in 2001

RANK	COMPANY	2000 SALES (US$ MILLION)	2001 SALES (US$ MILLION)
1.	Bayer + Aventis CropScience	5911	6086
2.	Syngenta	5888	5385
3.	Monsanto	3885	3755
4.	BASF	2228	3105
5.	Dow AgroSciences	2346	2612
6.	DuPont	2009	1917

Source: Agrow World Crop Protection News, Burrill and Co.

2. Seed Companies. Despite some overlap with agribusiness processors and grain handlers such as Cargill, seed firms have historically been a distinct breed as a result of these firms' specialization in the genetics of plant breeding and the production of hybrid and improved crop seeds. Corn hybrid seed, for example, has long been dominated in the U.S. by two firms: Pioneer Hi-Bred International and DeKalb Plant Genetics. Even the largest firms in the seed business have historically tended to specialize by crop type. Vegetable seed businesses have tended to succeed separately from hybrid corn seed and the other major row crops. With the consolidations brought by biotechnology, these boundaries have been blurred, but they have not gone away altogether. Table 4 compares recent sales figures of the top ten seed companies globally. Still, much of the seed industry consists of smaller players—often regionally specialized in particular crops—that undertake the tedious but essential labor of optimizing plant varieties to the multitudes of climactic and agronomic variables governing agricultural productivity region by region. Among the largest remaining independent seed companies are Limagrain and Advanta.

Table 4.
Top ten seed companies by global seed sales in 2001

RANK	COMPANY	2000 SALES (US$ MILLION)	2001 SALES (US$ MILLION)
1.	Du Pont (Pioneer)	1938	1920
2.	Monsanto (DeKalb)	1608	1707
3.	Syngenta	958	938
4.	Limagrain	677	764
5.	Savia (Seminis)	474	449
6.	Advanta	374	376
7.	KWS	309	349
8.	Delta & Pineland	301	306
9.	Sakata	272	231
10.	Dow (Mycogen)	185	215

Source: Phillips-McDougall

Seed sales are an essential commercial link for agricultural biotechnology, as seeds are the vehicle for delivering patented genetic material into the agricultural production process. Thus, firms that seek to create and capture value through the expression of genes in plants will seek market positions in seeds. The two technologies are complements, and this economic force has driven consolidation at the top end of the market between genetic trait developers, agrochemical firms and seed firms.[22]

Any firm that seeks to create and capture value with the expression of genes in plants necessarily seeks market position in seeds.

3. Academic and Government Research Institutions. Research universities and laboratories run by ministries of agriculture worldwide contribute enormously to the science and technology of agricultural biotechnology. In the U.S., state research universities of the Land Grant system, together with state Agricultural Experiment Stations and the federal Agricultural Research Service of the UDSA have shared long histories of driving the nations' development in agricultural genetics and pest control technologies, with estimated rates of return on the public investment averaging 20 to 25%. Several of the breakthroughs that gave birth to agricultural biotechnology occurred in academic labs: for

Those pharmaceutical firms that did have strong agricultural divisions have divested them.

example, the gene gun was developed at Cornell University and key work in agrobacterium-mediated plant cell gene transfer was done at Washington University. In addition to basic biological research, these state organizations also have extensive programs in plant breeding and crop variety improvement; for example, one of the largest strawberry breeding programs in the world is run by the University of California. In many cases these state institutions carry a public mandate to improve regional agricultural productivity through plant breeding and public germplasm release programs. Since the 1980s these engines of public research have become a more significant force in advancing commercial research and development through increased patenting and technology transfer, and perhaps most significantly, by giving rise to many of the independent biotechnology firms .

4. Independent Biotechnology R&D Firms. These consist primarily of small science-based firms with only a few to a few-hundred employees and with very high ratios of R&D spending per employee. Characteristically they are located near large research universities, and often headed by Ph.D. scientists. Some have made their start commercializing patented technology emerging from university based research. They are typically financed by venture capital in their early phases and remain privately held. While a few of the largest and most successful of these firms have gone public, they have had a high failure rate, and many have been sold to large corporations interested in acquiring specific research capabilities or complementary intellectual assets.

There have been two waves of biotechnology research and development startups in agriculture. The first wave began at the inception of the industry in the late 1980s and consisted largely of firms seeking to develop a particular set of genes or genetic traits into products, usually pest control sprays (biosys, Ecogen), genetically modified seeds (DNA Plant Technology, Calgene) or both (Mycogen). Other firms of the first wave staked out expertise in a particular type of crop (Agritope). These startups were largely unequipped to face costly and uncertain regulatory requirements, complex intellectual property environment, and the economies of scale in agricultural commodity markets. By the late 1990s, most of the first wave startups had either folded or been acquired by major corporations entering the market. The second wave, rising from the relentless pace of scientific development and the emergence of new genomics and bioinformatics tools, has focused on providing more up-stream R&D services based on specialized technological platforms, such as gene discovery (Mendel, Ceres) or in-plant molecular production systems (ProdiGene) that could be employed across a number of contexts.

5. Big Pharma. Most pharmaceutical firms that have ventured into agricultural biotechnology owned the agrochemical divisions or subsidiaries that became the core of the industry. During the first phase of consolidation and optimism in the mid 90s, many of these pharmaceutical firms came to style themselves as “life sciences” companies, seeking to fully express their core research and development competencies in the life sciences in pharmaceutical, nutritional, and agricultural businesses alike. Their traditional expertise in drug discovery and managing clinical trials through the regulatory gauntlet—supported by large programs in medical, biological, and chemical research—put them in what they hoped was a competitive position for the discovery and development of applications for plant biotechnology as well. Early on, European corporations seemed particularly prevalent in this group, including Ciba-Geigy, Sandoz, Zeneca, Hoechst, and Rhone-Poulenc. Early American firms included Upjohn, Eli-Lily, and American Home Products.

The fact that most of these names are now gone from the agricultural biotechnology scene shows that the pharma-ag life science model failed to create significant value. Those pharmaceutical firms that did have strong agricultural divisions have divested them. Upjohn decided early against the “life sciences” strategy and sold its interests in Asgrow Seed in the early 1980s. Lily divested its stake in DowElanco, the agricultural joint venture it shared with Dow which became Dow AgroSciences. Novartis and Zeneca spun off their respective agricultural divisions, which then merged to create the seeds and agrochemical firm Syngenta. Most recently Aventis (the merged Hoechst and Rhone-Poulenc), stronger in pharmaceuticals than it was is agriculture, sold its agricultural business to Bayer, a firm that is today arguably stronger in its chemicals business than in pharmaceuticals.

6. Agribusiness Companies and Cooperatives have made some efforts in biotechnology. The largest of these are multinationals, such as Cargill, and are primarily involved in purchasing, transporting, and processing commodity farm outputs, such as grains, soybeans, or sugar, into intermediary products, such as animal feed and food ingredients. Some of these agribusinesses also manufacture and distribute herbicides, pesticides, and fertilizers, and supply agricultural equipment and services specialized to a particular crop or type of agriculture. In the U.S., commodity groups and growers associations for specific crops such as citrus or rice occasionally band together to directly fund research in genetic improvement, often conducted at the state agricultural research universities, to be shared throughout that industry. This latter relationship has been strained since the advent of biotechnology, as universities have proven unable to clear regulatory and intellectual property hurdles in a cost-effective manner.

7. Food and Tobacco Corporations with strong research and development capabilities showed strong interest in the possibilities of agricultural biotechnology, at least until the mid 1990s. Product research and development has long driven such corporations as Procter & Gamble and Unilever to employ any technology appropriate to the improvement of their core consumer product and food brands. Campbell Soup and Frito-Lay focused small biotechnology efforts since the 1980s on improving the processing qualities of those particular crops on which their leading brands depend. Phillips Morris, U.S. Smokeless Tobacco, and other tobacco companies have interests in the quality of tobacco crops. Food companies' interest in pursuing research on genetically modified foods has never materialized into anything larger, largely as a result of doubts about the value contributed given pressure from consumer groups, particularly in Europe.

8. Paper and Paper Products companies have emerged on the fringe of agricultural biotechnology with major firms such as Westvaco and International Paper doing work to improve the genetics of their forestry trees. Their major interest, particularly in agroforestry settings where replanting is regularly practiced, is increasing speed of biomass accumulation and improving the pulp processing characteristics of wood, specifically by adjusting levels of cellulose and lignin.

R&D Trends and Commercial Applications

Bio-era has identified over 180 organizations—including corporations, universities, and government agencies—engaged in research and development in agricultural biotechnology. Each of these organizations has conducted one or more of the following activities:

- received U.S. patents for a technology relevant to agricultural biotechnology (1974-2002)
- had those U.S. patents cited by others, a measure of their patents' significance and value
- filed notifications or applied for permits to field test genetically modified organisms in the U.S. (1987-2003), and/or
- brought commercial agricultural biotechnology products to market (by 2003).

Table 5 indicates the share of the industry's overall research and development activity accounted for by each of these organizations based on an index comprised of these four measures of research and development activities.[23] Figure 2 illustrates the degree of concentration of research and development activities in plant biotechnology.

This analysis illustrates several important features of the current pattern of research and development

Bio-era has identified 180 organizations engaged in research and development in agricultural biotechnology.

within the industry:

- the top four firms account for 57% of research and development activities by these measures; the top eight firms account for 69%
- of the top 35 organizations engaged in biotechnology research and development, twelve are universities, collectively accounting for nearly 6% of overall research and development activity
- two government agencies, the U.S. Department of Agriculture and the Canadian Ministry of Agriculture and Food rank among the top 35 organizations
- pharmaceutical companies, that would have been significantly represented five years ago, are almost entirely absent from the list.

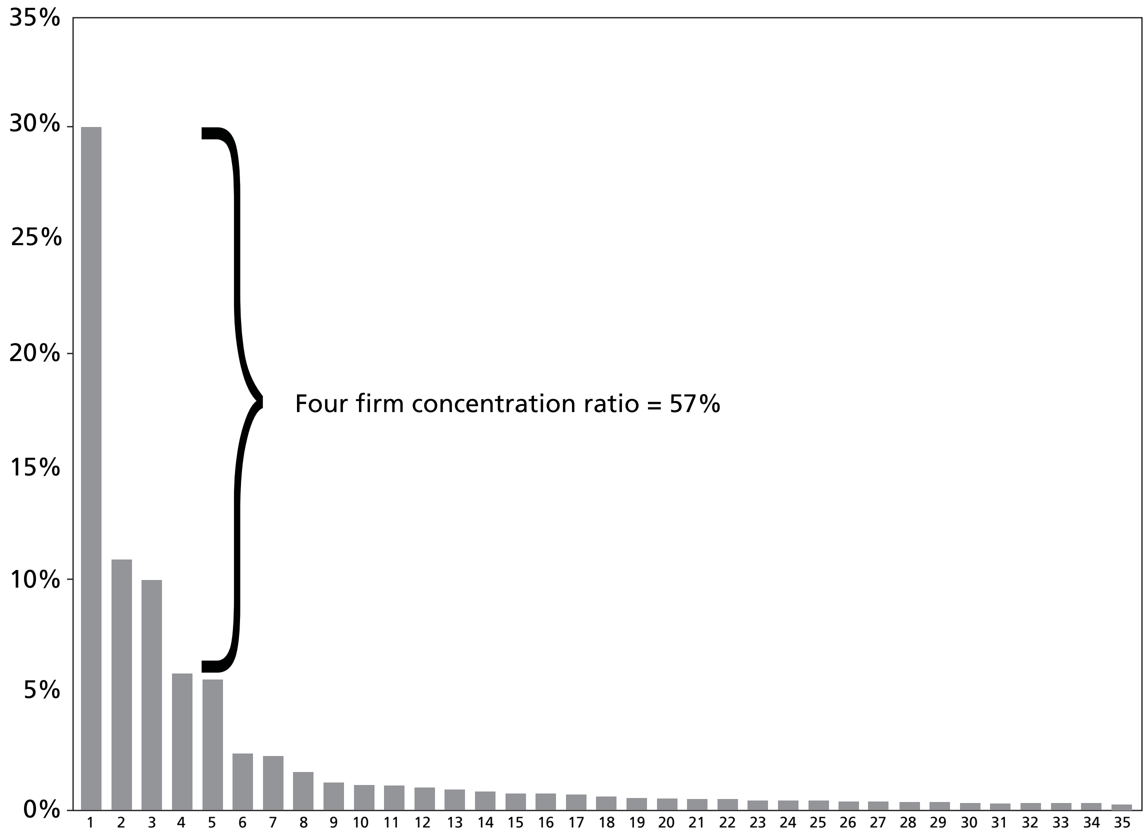
Developing a new genetically modified plant variety can take 6-12 years and can cost up to $300 million.

Among the reasons for the high degree of concentration in plant biotechnology research and development is the high cost and risk involved with these activities. The research and development pipeline in agricultural biotechnology typically has four phases: discovery, proof of concept, product development, and regulatory approval. From the first steps of discovery to final regulatory approval and product launch, the research and development process for a new genetically modified plant variety can take as long as from 6 to 12 years and can cost from $50 to $300 million. For each gene or trait explored in the discovery phase, the odds are roughly 1 in 250 that the gene or trait will make it into a commercial product. Then, at the end of this long cycle of investment and development, companies must face risks of market acceptance. In any case, research and development activity in this sector is likely to remain highly concentrated, especially in view of the complementarities among intellectual property assets discussed earlier in this report.

Table 5.
The top 35 R&D organizations in agricultural biotechnology

RANK	PARENT ORGANIZATION	SHARE OF INDUSTRY R&D OUTPUT
1.	Monsanto	29.82%
2.	Du Pont / Pioneer	10.98%
3.	Bayer / Aventis	10.14%
4.	Dow	5.81%
5.	Syngenta	5.80%
6.	Savia / Seminis	2.57%
7.	USDA	2.38%
8.	BASF	1.71%
9.	Cornell University	1.25%
10.	Stine Seed Farm Inc	1.15%
11.	Florigene	1.08%
12.	University of California	1.05%
13.	Exelixis	0.98%
14.	Iowa State University	0.91%
15.	Rutgers University	0.83%
16.	University of Guelph	0.79%
17.	Mitsui	0.75%
18.	Millennium Pharmaceuticals	0.67%
19.	University of Wisconsin	0.62%
20.	Novo	0.60%
21.	Cargill	0.53%
22.	Michigan State University	0.53%
23.	Texas A&M University System	0.49%
24.	Ministry of Agriculture and Agri-Food, Canada	0.48%
25.	Weyerhaeuser Co	0.48%
26.	Groupe Limagrain	0.46%
27.	Scotts Co	0.42%
28.	University of Florida	0.41%
29.	Kirin Brewery	0.39%
30.	University of Saskatchewan	0.39%
31.	ProdiGene	0.38%
32.	University of Idaho	0.37%
33.	Westvaco	0.36%
34.	Bejo Zaden	0.33%
35.	North Carolina State University	0.33%

Figure 2. The distribution of R&D output measures among the top 35, with four firm concentration ratio



The biotechnology-based agricultural products on the market today represent only the tip of an iceberg beneath which looms a vast amount of research and development activity. This can be illustrated by comparing the numbers of genetically modified crop varieties actually growing (Table 6) with the much larger body of technologies that have been approved for field testing in the U.S. over the last five years (Table 7).

While genetically modified crops accounted for about for 53 million hectares grown worldwide in 2001 and 59 million in 2002, the overwhelming majority of this acreage is accounted for by crop-protection modifications within four major crops: corn, soybeans, cotton and rapeseed. Small acreages of commercial crops are now being grown in several countries with genetically modified traits aimed at product quality, disease or pathogen resistance, or agronomic properties. The broad distribution of activity in recent field trials, which includes more than a dozen crops and several dozen categories of traits from pest resistance to pharmaceuticals, indicates the wide range of new crops just over the horizon. The development activity with respect to these new traits is described below.

Notably, the types of companies involved in various avenues of development vary widely according to the size of commercial opportunity, the "willingness to pay" of the potential beneficiaries, and the strategic relationship of the market opportunity to the existing product lines of the developers. This suggests that the ongoing shifts in industry structure will have significant long term consequences for what research gets done and who does it.

Table 6. The Tip of the Iceberg: global coverage in 2001 of the ten leading genetically modified organisms, by technology type (million hectares)

Technology Type	Corn	Potato	Soybean	Cotton	Wheat	Tomato	Rice	Rapeseed	Alfalfa	Beet	Tobacco	Total
Insect Resistance	**7.7**	>>		**4.3**								**11.5**
Herbicide Tolerance	**3.9**		**33.3**	**4.9**	>>			**2.7**		>>		**44.8**
Product Quality												
Disease Pathogen Resistance			>>					>>				>>
Agronomic Property		>>										>>
Other Technology												
Marker												
Total per Organism	**9.8**	>>	**33.3**	**6.8**	>>			**2.7**		>>		**52.6**

Table 7. The Rest of the Iceberg: approved U.S. field trials from 1997 to 2002 in ten leading genetically modified organisms, by technology type and trait

Technology Type	Trait	Corn	Potato	Soybean	Cotton	Wheat	Tomato	Rice	Rapeseed	Alfalfa	Beet	Tobacco	Total
Insect Resistance	Coleopterra	781	23	2	2			1	1				810
	Lepidoptera	457	5	42	172		7	2	15			3	703
	Colorado Potato Beetle	1	151										152
	European Corn Borer	21											21
	Other	2										2	5
Insect Resistance Total		**1262**	**179**	**44**	**175**		**7**	**3**	**16**			**5**	**1691**
Herbicide Tolerance	Glyphosate	281	46	16	69	137	10	34	29	98	65	1	786
	Phosphinothricin	304		38	47	1	5	47	11	3	28	2	489
	Other	53		22	1			10	2		2	1	91
	Imidazolinone	41		11				1					53
	Isoxazole	23		19									42
Herbicide Tolerance Total		**702**	**46**	**106**	**117**	**141**	**15**	**92**	**42**	**101**	**95**	**4**	**1461**
Product Quality	Protein content	151	1	39		11			1				203
	Carbohydrate content	105	50	2	8	3	15	8					191
	Other	58		38	7	4	17	2	2	7			135
	Ripening	2	59		7		27			4		5	104
	Micronutrient content	28	13	13		1	14		2	4		23	98
	Oil Content	37		21	2				27				87
Product Quality Total		**381**	**123**	**113**	**24**	**19**	**73**	**10**	**32**	**15**		**28**	**818**
Disease Pathogen Resistance	Fungus	113	47	41	3	21	15	4	7			4	225
	PVY virus		122				7					5	134
	Other virus	5	26	7		27	27				4	20	116
	PLRV virus		98										98
	Bacterial		11				13	5				2	31
	Nematode		1				1						2
Product Quality Total		**118**	**305**	**48**	**3**	**48**	**63**	**9**	**7**		**4**	**31**	**636**
Argonomic Property	Yield	111		13	13	10	6	5	4				162
	Fertility/Sterility	96		1				1	14				112
	Other	19		16	3	2	1			1		1	43
	Stress Tolerant	20			8	5	3		2				38
	Nitorgen use	22		1		7				3		2	35
Argonomic Property Total		**268**		**31**	**24**	**24**	**10**	**6**	**20**	**4**		**3**	**390**
Other Technology	Novel protein	94		7		2		4				13	184
	Other	48		4			6	1					16
	Pharmaceutical	46					1	7					12
Other Technology Total		**188**		**11**		**2**	**7**	**12**				**13**	**390**
Marker	Visual marker	153	3	5	1	1	1	2	2			13	184
	Other	14	1			1							16
	Antibiotic resistance	4	4			1		3	3				12
Other Technology Total		**171**	**8**	**5**	**1**	**3**	**1**	**5**	**5**			**13**	**212**
Other Technology Total		**3090**	**661**	**358**	**344**	**237**	**176**	**137**	**122**	**120**	**99**	**99**	**5443**

Herbicide tolerance

This technology has proven to be the "killer app" of plant biotechnology in the industry's initial phase. Given the high specificity of plants' engineered tolerance for certain herbicides, promoting these traits has been a natural focus of the agrochemical companies that produce those herbicides. The popularity of this trait has attracted the interest of independent seed companies as well. Herbicide tolerance has been quickly commercialized because it is a relatively easy genetic trait to engineer into a plant, often involving just one enzyme. It will not be surprising if certain forms of herbicide tolerance become generalized and inexpensive standard features of crop seeds. The technology is only as good as the herbicide, however, and the value of any chemical-gene combination will be strongly influenced by the emergence of herbicide tolerance among weed populations. Producers are already urging growers to apply a diversity of weed control methods, to prevent undue exposure of weed populations to any one technology.

Producers are already urging growers to apply a diversity of weed control methods, to prevent undue exposure of weed populations to any one technology.

Insect resistance

Biopesticides. Biopesticide sprays derived from the *bacillus thurengiensis*, a naturally occurring bacteria, were commercially available as early as the 1950s. These products were natural product line extensions for existing agrochemical and seed businesses. By the 1990s, as biological products became less expensive to develop compared to new chemical pest control products, both small biotechnology firms and large agrochemical producers were found developing and marketing biopesticide products to farmers.

Insect Resistance. The same compounds that act as effective biopesticides, such as the Bt toxin, can be genetically engineered into crop plants to make them resistant to pests. Agrochemical firms were initially motivated to incorporate insect resistance into plants because development and regulatory approval of these plant varieties promised to be less costly than introducing new chemical pesticides. They were also assumed to provide a long term response to increased environmental regulation of pesticides, providing an environmentally more sophisticated and beneficial approach to controlling pests. Insect resistance was also a focus of public research organizations, with an environmental aim at reducing the overall use of chemicals in agriculture.

Just as with herbicides, the value of insect pest control technology will be strongly influenced by the emergence of resistance among insect populations. Future generations of insect resistance technology may become more diverse in mechanisms as molecular targets become easier to identify with advances in discovery technologies. Such diversification would help to counter development of resistance.

Product quality

Protein, Carbohydrate, and oil content.
Biotechnology can be used to adjust the quantities of specific kinds of proteins, carbohydrates, and oils in crop food plants. This concept was first pursued commercially by large seed firms, such as Poineer, to boost the quality of animal feed, engineering deficient essential amino acids like lysine and methionine into feed grains. The improvement of the macronutrient content of food is finding other specialty applications for humans consumption. One promising area is in the modification vegetable oils, whereby the genetics that code the length and saturation of fatty acid chains of the vegetable oil are customized to produce healthier oils.

Micronutrient and secondary metabolite content.
One of the most famous products of agricultural biotechnology is golden rice, a grain engineered to contain high levels of beta-carotene to combat vitamin A deficiency. The levels of other naturally occurring plant compounds such as caffeine and nicotine can also be decreased (or increased) by modifying the genes that govern the production of these compounds.

Improved ripening and shelf life. The compounds and chemical pathways in fruits and vegetables responsible for ripening and softening are now reasonably well understood and biotechnologies are available that can slow down key steps in the process resulting in tomatoes, bananas, and other fruits with longer shelf lives.

Improved flavor and morphology. As with improving shelf-life, compounds in the plant can be eliminated or increased depending on their effect on the appeal of the fruit or vegetable as a food. The phenotypic expression of size, shape, and color of the produce can be enhanced by appropriately altering the producing plant's genotype.

Improved processing characteristics. For food processing industries, certain material-content levels or other attributes of the harvested crop are considered "ideal." For example, in processing potatoes, a high starch content of 25% is preferred to a more naturally occurring starch content of 21-22%. Monsanto has succeeded in developing a high starch potato that meets the 25% criterion. Other crops developed for improved processing are tomatoes—for use in sauce and paste—and paper pulp—to make naturally occurring lignin easier to remove from cellulose. While food-processing and paper-milling firms stand to benefit from production cost savings and improved final products, they have done only some of the biotechnology work themselves, tending to work closely with biotechnology research firms as contract research providers.

Pathogen and disease resistance

Resistance to viruses and other pathogens. This is a trait of crop plants that was originally pursued by seed firms to improve the vigor and health of their product lines and by public sector plant breeders in the general interest of certain agricultural sectors. Biotechnological research to these ends constitutes a significant focus of public research organizations.

Plant diagnostics. Increasing farmers' ability to quickly detect and diagnose infestations and crop disease can greatly reduce costs and risk. Biological assay and diagnostic test kits developed through the application of biotechnologies are easy for small research firms to develop and market independently, and it is an area of plant biotechnology that is close to diagnostic technologies being developed for human health applications. Given that the market size is deemed to be relatively small, plant diagnostics tends to be the purview of small biotech firms.

Agronomic properties

Improving crop plant qualities such as resistance to drought or climate stress, increased nitrogen utilization, or better adaptation to inter-cropping was one of the earliest motivations for crop biotechnology research in the public sector. Seed companies have always sought such quality improvements in their varieties through breeding and continue now with the added tools of biotechnology.

Improving crop plant qualities, such as resistance to drought was one of the earliest motivations of plant biotechnology research in the public sector.

Higher primary plant productivity and higher product yield. Biotechnology brings new techniques and tools to bear to increase yields of traditional large acre crops. A few small biotechnology and agricultural-products firms are also specializing in improving the yield and quality of particular specialty crops.

Fertility control and male sterility. Control over the fertility of plants is sensitive business. Early work by the USDA Agricultural Research Service, Delta and Pine Land, and Monsanto on mechanisms to induce seed sterility in the second generation—a sort of copy protection intended to prevent the replanting of seed containing proprietary genetics—was met with strong resistance from farm advocates. Nonetheless, the challenges posed by controlling unwanted and unintentional gene flows may breathe new life into these traits for genetically modified crop plants.

One important area of agronomic properties is the improvement of hybrid production by engineering male sterility into the hybrid line so that the necessary parental line crosses may be executed with much less labor intensity. Commercial applications will largely benefit seed companies, as male sterility will lower breeding costs, reduce breeding time and increase hybrid product lines.

Other non-food applications

Novel and pharmaceutical protein production. In some cases plants may be an economically more efficient way to synthesize proteins in quantity. Companies such as Dow, Epicyte, Prodigene, and Monsanto are using crops to manufacture for herpes, HIV, respiratory viruses, and other applications. Epicyte is developing an anti-sperm antibody for contraceptive use. Prodigene is protein sweeteners, therapeutic proteins, and oral vaccines against enterotoxigenic E. coli.

The future scope of "biopharming" is uncertain, but expectations run high. Gary Cardineau of Dow Agrosciences estimated in 2001 that biopharming could be a $200 billion industry within 10 years. Epicyte Pharmaceutical estimates that it will be able to produce the same quantity of drugs from 200 acres of corn that a $400 million factory could produce in a year.

Biomaterial and biochemicals production. New approaches are being developed to produce a wide variety of industrial products—from polymers and plastics to specialty chemicals, dyes, lubricants, flavorings, antioxidants and immune system stimulants, vitamins, and pharmaceutical compounds. CargillDow is producing polylactide from corn, for use in packaging materials, and a wide variety of fiber applications. Prodigene is using plants to produce industrial enzymes.

Emerging non-food biotechnology applications in agriculture will be the subject of future bio-era reports.

Appendix. Research and Development Activity in Agricultural Biotechnology

	INDUSTRY R&D MEASURES				
Parent Organization	US plant biotech patents	Citations made to US plant biotech patents	GM field trials	GM products commer-cialized	Share of industry R&D measures
Abbott and Cobb	0	0	2	0	0.01%
Advanta	30	11	21	0	0.29%
Agraquest Inc	5	7	0	0	0.04%
AgraTech Seeds	0	0	3	0	0.01%
AgReliant Genetics	0	0	11	0	0.04%
Agricultural Genetics Company Limited	16	58	0	0	0.21%
Agrium	1	6	0	0	0.02%
Agrogene	3	3	0	0	0.02%
Ajinomoto	14	64	0	0	0.21%
Applied Phytologics Inc	4	0	21	0	0.11%
ArborGen	0	0	13	0	0.05%
Asahi	7	15	0	0	0.07%
Atlantic Richfield Co	4	15	0	0	0.05%
Auburn University	3	19	5	0	0.07%
Bar-Ilan University	2	14	0	0	0.04%
BASF	46	176	35	3	1.71%
Battelle Development Corp	4	33	0	0	0.09%
Bayer / Aventis	198	447	502	19	10.14%
Bejo Zaden	1	0	0	1	0.33%
Betaseed	0	0	46	0	0.18%
CAMBIA Biosystems LLC	4	34	0	0	0.09%
Campbell Soup Co	5	7	2	0	0.05%
Cargill	28	102	41	0	0.53%
Centre National De La Recherche Scientifique (CNRS), France	7	3	0	0	0.05%
China National Science Council	5	19	0	0	0.07%
China National Seed Corp	2	13	0	0	0.04%
Cold Spring Harbor Laboratory	4	3	1	0	0.03%
Colorado State University	3	8	5	0	0.05%
Commonwealth Scientific & Industrial Research Organisation (CSIRO), Australia	12	11	0	0	0.10%
Cornell University	60	231	31	1	1.25%
CropTech Development Corp	1	1	16	0	0.07%
Dairyland Seed Co	2	0	1	0	0.02%
Danisco AS	24	51	0	0	0.25%
Delta and Pine Land Co	18	13	4	0	0.15%
Demegen Inc	0	0	2	0	0.01%
Dow	246	1884	123	1	5.81%
Dry Creek	1	0	6	0	0.03%
DSM	24	66	0	0	0.27%
Du Pont / Pioneer	597	1165	467	10	10.98%
Duke University	3	18	5	0	0.07%
Ecogen	5	0	0	0	0.03%
EcoScience	12	3	0	0	0.08%
EDEN Bioscience	2	0	0	0	0.01%
Exelixis	18	19	48	2	0.98%
Florigene	14	17	0	3	1.08%
FMC Corp	11	25	0	0	0.12%
Forage Genetics International	0	0	6	0	0.02%
Gargiulo	0	0	30	0	0.12%
Genesis Research & Development Ltd.	4	4	0	0	0.03%
Golden Harvest Seeds	0	0	7	0	0.03%
Great Lakes Hybrids	0	0	4	0	0.02%
Groupe Limagrain	19	16	78	0	0.46%
Hawaii Agricultural Research Center	0	0	8	0	0.03%
Hebrew University of Jerusalem	15	45	0	0	0.18%
Institut National De La Recherche Agronomique (INRA), France	10	17	0	0	0.09%
Institut Pasteur, France	19	19	0	0	0.16%
Integrated Plant Genetics	0	0	2	0	0.01%
Hebrew University of Jerusalem	15	45	0	0	0.18%
Institut National De La Recherche Agronomique (INRA), France	10	17	0	0	0.09%

	INDUSTRY R&D MEASURES				
	US plant biotech patents	Citations made to US plant biotech patents	GM field trials	GM products commer-cialized	Share of industry R&D measures
Institut Pasteur, France	19	19	0	0	0.16%
Integrated Plant Genetics	0	0	2	0	0.01%
Parent Organization					
International Paper Co	12	44	6	0	0.18%
Invitrogen Corp	8	20	0	0	0.09%
Iowa State University	39	154	97	0	0.91%
J R Simplot Co	7	5	0	0	0.05%
Japan Tobacco Inc	22	44	0	0	0.22%
John Innes Centre	6	0	0	0	0.04%
Kansas State University	4	2	7	0	0.06%
Kirin Brewery Co Ltd	19	148	0	0	0.39%
Large Scale Biology Corp	25	50	7	0	0.28%
Louisiana State University	15	43	24	0	0.27%
Massachusetts General Hospital (MGH)	20	70	0	0	0.26%
Massachusetts Institute Of Technology (MIT)	12	93	0	0	0.25%
Max Planck Institute	20	12	3	0	0.16%
Maxygen Inc	1	39	0	0	0.08%
McGill University	6	14	0	0	0.06%
Mendel Biotechnology Inc	1	0	2	0	0.01%
Meristem Therapeutics	1	0	2	0	0.01%
MGI Pharma Inc	10	331	0	0	0.67%
Michigan State University	37	107	26	0	0.53%
Michigan Technological University	2	2	4	0	0.03%
Midwest Research Institute	8	16	0	0	0.08%
Ministry of Agriculture and Agri-Food, Canada	21	15	0	1	0.48%
Ministry Of Agriculture Forestry and Fisheries, Japan	17	5	0	0	0.12%
Ministry Of Agriculture, Israel	5	5	0	0	0.04%
Ministry of Industrial Science and Technology (MITI), Japan	6	20	0	0	0.07%
Ministry Of Industry and Trade, Israel	1	3	0	0	0.01%
Ministry Of Natural Resources, Canada	6	11	0	0	0.06%
Mississippi State University	6	1	1	0	0.04%
Mitsubishi	9	26	0	0	0.10%
Mitsui	46	246	1	0	0.75%
Monsanto	647	2832	2855	29	29.82%
Montana State University	2	6	17	0	0.09%
National Research Council (NRC), Canada	10	9	0	0	0.08%
NC+ Hybrids	0	0	7	0	0.03%
New Mexico State University	1	0	10	0	0.05%
New Oji Paper Co Ltd	5	2	0	0	0.04%
North Carolina State University	28	50	14	0	0.33%
North Dakota State University	2	1	4	0	0.03%
Novaflora Inc	1	1	0	0	0.01%
Novo	67	92	0	0	0.60%
Oglevee Ltd	6	9	0	0	0.05%
Ohio State University	6	24	10	0	0.12%
Oregon State University	1	3	52	0	0.22%
Pennsylvania State University	9	8	3	0	0.08%
Pepsico	2	7	4	0	0.04%
Philip Morris	5	4	0	0	0.04%
Plant Genetics Inc	4	57	2	0	0.14%
Plant Sciences Inc	0	0	4	0	0.02%
PlantGenix	0	0	2	0	0.01%
ProdiGene Inc	2	0	93	0	0.38%
Purdue Research Foundation	17	40	16	0	0.24%
Pure Seed Testing Inc	1	0	2	0	0.01%
R J Reynolds Tobacco Co	1	1	2	0	0.02%
Rijksuniversiteit Leiden	6	58	0	0	0.14%
RIKEN	5	5	0	0	0.04%
Ring Around Products Inc	8	91	0	0	0.22%
Roche	21	69	0	0	0.26%
Rockefeller University	11	60	0	0	0.18%
Rutgers University	22	175	95	0	0.83%
Sakata Seed	5	3	0	0	0.04%

INDUSTRY R&D MEASURES

	US plant biotech patents	Citations made to US plant biotech patents	GM field trials	GM products commercialized	Share of industry R&D measures
Salk Institute	22	66	0	0	0.26%
Samuel Roberts Noble Foundation Inc Parent Organization	1	0	14	0	0.06%
Sapporo Breweries	10	13	0	0	0.09%
Savia / Seminis	23	326	221	3	2.57%
Scotts Co	0	0	106	0	0.42%
Scripps Research Institute	5	17	0	0	0.06%
Sembiosys Genetics Inc	3	2	1	0	0.03%
Shin-Etsu	6	8	0	0	0.05%
Showa	4	30	0	0	0.08%
Solvay	6	38	0	0	0.11%
Southern Illinois University	1	1	11	0	0.05%
Stanford University	5	5	62	0	0.28%
State University of New York	2	14	13	0	0.09%
Stine Seed Farm Inc	92	129	82	0	1.15%
Sumitomo	28	38	0	0	0.25%
Syngenta	352	837	190	4	5.80%
Takara Shuzo Co Ltd	11	13	0	0	0.09%
Takeda Chemical Industries Ltd	7	6	0	0	0.06%
Takii	4	0	6	0	0.05%
Texas A&M University System	15	177	17	0	0.49%
Texas Tech	7	0	23	0	0.14%
Tuskegee University	0	0	7	0	0.03%
Unilever	33	51	4	0	0.32%
United States Sugar	0	0	7	0	0.03%
University of Arizona	9	8	28	0	0.18%
University of British Columbia	13	76	0	0	0.22%
University of California	85	159	54	0	1.05%
University of Chicago	11	29	15	0	0.18%
University of Connecticut	0	0	6	0	0.02%
University of Florida	25	50	40	0	0.41%
University of Georgia	11	67	28	0	0.30%
University of Guelph	9	403	0	0	0.79%
University of Hawaii	8	6	16	0	0.12%
University of Idaho	5	13	81	0	0.37%
University of Illinois	3	9	13	0	0.09%
University of Kentucky	12	4	45	0	0.26%
University of Minnesota	18	63	20	0	0.31%
University of Missouri	7	9	2	0	0.07%
University of Nebraska	5	9	22	0	0.13%
University of North Carolina	0	0	9	0	0.04%
University of Rhode Island	1	3	5	0	0.03%
University of Saskatchewan	5	23	0	1	0.39%
University of South Carolina	1	1	1	0	0.01%
University Of Tennessee	3	1	3	0	0.03%
University of Texas	7	28	0	0	0.10%
University of Washington	2	1	1	0	0.02%
University of Wisconsin	38	163	21	0	0.62%
US DHHS	6	93	0	0	0.21%
USDA	110	589	154	0	2.38%
UST Inc	0	0	22	0	0.09%
Vanderbilt University	5	20	0	0	0.07%
Vector Tobacco	0	0	22	0	0.09%
Ventria Bioscience	0	0	4	0	0.02%
Virginia Tech	3	1	4	0	0.04%
Washington State University	21	9	19	0	0.23%
Washington University	8	33	0	0	0.11%
Weizmann Inst	6	13	0	0	0.06%
Westvaco	15	72	33	0	0.36%
Weyerhaeuser Co.	22	185	1	0	0.48%
W-L Research	0	0	3	0	0.01%
WyFFels Hybrids	0	0	4	0	0.02%
Yoder Brothers Inc	3	1	1	0	0.02%

Notes

1 Neil E. Harl, presentation to the Annual Meeting of the American Society of Farm Managers and Rural Appraisers, February 6, 2003.

2 W. Brian Arthur, personal communication, December 10, 2002.

3 Canadian Grain Industry Working Group on Genetically Modified Wheat, "Market Impact and Potential Introduction of Genetically Modified Wheat: Key Messages and Outline of Proposed Market Impact Test," February 5, 2003.

4 Harl, [1].

5 Matin Qaim and David Zilberman, "Genetically Modified Crops in Developing Countries," *Science*, February 7, 2003 (vol. 299) p. 900-01.

6 Mark Dibner, ed., *Biotechnology Guide U.S.A.*, Institute for Biotechnology Information, (MacMillan,:1999).

7 Phillips-McDougal, 2002.

8 Clive James, "Global Status of Commercialized Transgenic Crops: 2002", ISAAA Briefs No. 27: Preview, www.isaaa.org.

9 Monsanto, 2002.

10 Eamonn Kelley and Peter Leyden, What's Next: Exploring the New Terrain for Business (Perseus: 2002), p. 209.

11 Gregory D. Graff, Gordon C. Rausser, and Arthur A. Small, "Agricultural Biotechnology's Complementary Intellectual Assets", *Review of Economics and Statistics,* forthcoming May 2003.

12 Deborah Delmer, Jack Clough, and Rex Raimond, "Public Sector Intellectual Property Resource for Agriculture—pSIPRA," Rockefeller Foundation and Meridian Institute, January 2003

13 Dr. Ian Heap, International Survey of Herbicide Resistant Weeds, www.weedscience.org, February, 2003.

14 Tom Clarke, "Corn Could Make Cotton Pests Bt Resistant," *Science Update*, January 2, 2003, www.nature.com/nsu/021202/021202-2.html

15 For further discussion see: Murray Fulton and Konstantinos Giannakas, "Agricultural Biotechnology and Industry Structure," *AgBioForum*, vol. 4, no. 2 (2001), pp. 137-151.

16 James F Oehmke, Biotechnological R&D Races, Industry Structure, and Public and Private Sector Research Orientation, AgBioForum, vol. 4, no. 2 (2001), pp. 105-114.

17 The USDA Animal and Plant Health Inspection Service regulates GMO field trials. The U.S. field trial data is publicly available online at http://www.isb.vt.edu.

18 Monsanto had its own pharmaceutical division Searle. Dow was in joint venture with Eli Lilly. Syngenta's parents were Zeneca and Novartis, which itself was the merger of Ciba-Geigy and Sandoz.

19 Monsanto bought Agracetus and Calgene, Dow acquired Mycogen, and Zeneca bought Mogen.

20 Monsanto bought Asgrow, DeKalb, Holdens, and Corn States. Dow got some seed business in the deal with Mycogen. Du Pont acquired Pioneer. Syngenta inherited solid seed businesses from Zeneca and Novartis, which had both moved into seeds early, respectively incorporating such names as Garst and Northrup King.

21 Syngenta joined together similar biotech, seed, and chemical profiles being cast off by Zeneca and Novartis in November 2000. Bayer acquired Aventis CropScience in October 2001, as it was spun off from Aventis' pharmaceutical business. Monsanto divested from Pharmacia in August 2002, stripped of its former pharmaceutical business

22 See Graff, Gregory, Amir Heiman, and David Zilberman, "University Research and Offices of Technology Transfer," *California Management Review*, November 2002

23 The four R&D measures are weighted equally. For example, having 10 percent of industry patents is just as significant as having 10 percent of commercialized products. SHARE OF INDUSTRY R&D OUTPUT = (SHARE OF INDUSTRY PATENTS + SHARE OF INDUSTRY PATENT CITATIONS + SHARE OF INDUSTRY FIELD TRIALS + SHARE OF INDUSTRY COMMERCIALIZED PRODUCTS) / 4.