CROP PROTECTION INDUSTRY – RETOOLING FOR A NEW TOMORROW

Elmo Beyer and Forrest Chumley of DuPont Agricultural Enterprise, Wilmington, Delaware, in the USA look forward to the impact which new technologies will have on the crop protection business

Introduction

Catalyzed by strong competitive forces in crop protection chemicals and promising new business opportunities in biotechnology, the agrochemical industry is currently undergoing a major restructuring and metamorphosis. This transformation is characterized by mergers, acquisitions, joint ventures and alliances. Although such changes have been underway for some time, their intensity has dramatically increased in recent years.

A key impetus for this rapid transformation is the highly competitive nature of the agrochemical market fuelled by slow market growth, reduced rate of technological innovation and depressed farm prices. Many analysts believe these conditions are not likely to subside soon because they believe there are too many companies, spending too much money, pursuing too few opportunities. Broad-based and costly R&D programs are needed to achieve breakthroughs in pest control technology. Without such breakthroughs, companies are finding it increasingly difficult to remain viable and grow, especially in an industry where real growth has averaged only 1.2% per annum since 1990. As a result, many well-known agrochemical company names have disappeared and are being replaced by fewer, but larger entities such as Aventis, Syngenta and Dow AgroSciences.

A second major impetus for rapid change is biotechnology. Many of the dominant players are using biotechnology as a springboard to create new market opportunities beyond traditional crop protection chemicals. By acquiring or forming joint ventures with companies in the seed and downstream food and feed markets, these players clearly intend to create global integrated agrobusiness enterprises. During the last two years alone, Monsanto and DuPont have spent over 18 billion dollars pursuing this strategy.

Retooling of research for more effective new product discoveries is also an integral part of the current restructuring. World-class competencies in chemistry and genetics are being linked synergistically through biotechnology to build robust, flexible and responsive technology platforms to create new product offerings. Researchers are designing the next generation of crop protection chemicals as well as genetically engineering crops and biologicals for improved pest control, yield and quality. These genetically enhanced products are targeted not only at farmers but also at livestock producers, processors and other end-users of foods, feeds and biomaterials.

Over the next 30 to 40 years, agricultural productivity must be increased by 3-fold to feed the burgeoning world population which is expected to reach 8.5 billion near the middle of the next century. With limited arable land, major breakthroughs in technology will be essential to achieve such a daunting task.

Feeding the world's population in the 21st century

Currently, world population is growing by about 80 million per year, increasing the annual demand for grain by about 26 million tons. The increase in population growth is not expected to stabilize until around 2035, resulting in 2.5 billion more people to feed.[1] This increase, and the concomitant demand for grain, especially corn, wheat, rice and soybeans, will continue to place tremendous pressure on today's global agricultural production systems. Moreover, meeting the challenge of increased grain production cannot wait, since in 1996–1998 world grain reserves stood at the lowest levels ever recorded, only enough to meet global needs for less than 60 days.[2] The demand for grain is increasing as the standard of living in developing countries improves because of the desire of many people to eat more meat and animal products. As more meat is consumed, the requirement for feed grains dramatically increases since about 7 pounds of grain are required for each pound of beef produced. Thus, as affluence increases in the developing nations, a 40% increase in world population could translate into a need for a 200-300% increase in grain production. It is paramount that over the next decade agricultural production keeps pace with growing population because of the strong evidence that meeting or exceeding basic requirements for food is an essential first step in moderating population growth.

Historically, farmers have met the need for increased production by clearing and cultivating new land and by increasing the unit productivity of the land being farmed. In today's world, expanding the area under cultivation is no longer a viable option. Indeed, in many areas around the world, societies are struggling to prevent the loss of prime farmland. In India and China, for example, combined population growth of nearly 750 million by 2030 is expected to result in a demand for construction of nearly 100 million additional residential units. Moreover, economists are projecting the simultaneous construction of 1.5–2 million new factories. Because of the proximity between prime agricultural land and the major centers of growth and development, it is inevitable that much of the land for new construction will continue to come at the expense of farmland. In 1950, per capita grain area peaked at about 0.23 hectares per person; and by 2030, it will be one-third this amount or 0.08 hectares per person.[3] A global struggle is clearly underway to produce more food on a shrinking arable land base.

Increasing the productivity of existing farmland offers the only realistic hope for meeting the food production challenges of the next century. The modern green revolution has resulted in the basic food sufficiency enjoyed today by most of the world's population. Since 1950, global average grain yields per hectare have increased by a factor of nearly three.[4] This increase has been achieved by development of new crop varieties that are highly responsive to a wide range of improved agronomic management practices for maximum yield. Some of these new varieties have shorter days to maturity permitting double or even triple cropping in the tropics. Modern crop protection methods, along with the optimum use of other inputs, have been essential for realizing the full potential of these new varieties.

It is estimated that the dramatic increase in yields since the 1950s has spared the clearing of over 12 million square miles of marginal land which otherwise would have been converted to low-yield farming and livestock production.[5] Further increases in the efficiency of food production systems are not only essential to meeting global nutritional needs but are also the key to halting much of the deforestation that takes place in environmentally sensitive areas, with attendant wildlife habitat destruction and loss of biodiversity.

Clearly, the challenge of the next century is to achieve a step-change increase in the productivity of the world's agricultural systems and in the quality and affordability of the food they produce. As agricultural supply and demand tighten, government policies must prevent rising prices from imposing severe hardships on some of the developing countries. At the same time, there must be adequate incentives to ensure continued investments in agricultural systems by the private sector. Increased government funding for research will be critical, especially in those areas that have been neglected or underdeveloped. Many of the step-change improvements for increased productivity and food quality will come from dramatically enhanced crop production technologies. Because of their proven record in developing new agricultural technology and business systems on a global basis, the world's major agricultural chemical and genetics-based companies will certainly lead the way. Many of these companies are already undergoing the changes needed to prepare them for the opportunities and challenges of the 21st century.

Competition and restructuring in the crop protection industry

The crop protection industry is led by a relatively small number of large and highly competitive companies. For example, in 1997 the top 10 agrochemical companies accounted for approximately 80% of the $30 billion worldwide crop protection sales. The global agrochemical market is relatively mature with real growth averaging only 1.2% per year since 1990.[6] In this marketplace, a company's success comes from the introduction of new products, which can gain market share only if they offer sufficient customer and societal benefits to displace existing products. Reaching these attribute targets with new product offerings is increasingly difficult, time consuming and costly. Industry-wide, more than $125 million in total costs are accumulated by the time a new product generates its first sales, and it is not uncommon for the discovery and development phase to last 8 or 9 years. The cost of bringing new products to the marketplace is further increased by ever more challenging societal demands leading to more stringent government regulatory requirements.

The industry continues to undergo a good deal of volatility due to rapid changes in global economics, regulations and competition, especially competition from generic producers and companies with new, cost-effective technology. For example, generic competition over the past few years has reduced the price of chlorpyrifos, chlorsulfuron, isoproturon and trifluralin by 20% or more.

Changes in regulations can be a problem or an opportunity. For example, in the United States, the Food Quality Protection Act (FQPA), passed in 1996, has mandated a review of existing pesticides. The FQPA establishes new standards for exposure levels for infants and children and places new emphasis on "estrogenic effects" and other reproductive endpoints. Such changes are threatening to cause the blanket cancellation of product registrations for broad classes of widely used crop protection products, such as the organophosphate insecticides. Citing public concerns about possible neurological effects associated with long-term, low-level exposure, the UK Ministry of Agriculture has also announced a review of 15 organophosphate and 9 carbamate insecticides.[7] A draconian move to cancel broad classes of crop protection chemicals could create a $9 billion opportunity for agrochemical producers to bring new technologies to the market (Table 1). Whether replacement will come gradually,

Table 1. Opportunities for crop protection chemical class replacement

Class	Size	Perceived risk issue
Triazines	$1.5 Billion	Groundwater Accumulation
Quaternary ammonium	$0.3 Billion	Acute Toxicity
Organophosphates	$3.3 Billion	Acute toxicity; estrogenic effects
Carbamates	$1.5 Billion	Acute toxicity; estrogenic effects
Benzimidazoles	$0.4 Billion	Pest resistance
EBDC's	$0.7 Billion	Toxicity
Acetanilides	$1.5 Billion	Groundwater accumulation
TOTAL	$9.2 Billion	

Table 2. History of consolidation in the agrochemical industry

Year	Event
1986	Dupont buys Shell Development Corporation, US ag business
1987	ICI buys Stauffer's ag business
1988	Chevron buys PPG's ag business
1988	Sumitomo & Chevron form Valent joint venture
1989	Dow and Eli Lilly form Dow-Elanco joint venture
1990	Ciba-Geigy buys Dr. Maag
1991	Merck Crop Protection buys Pfizer's ag business
1992	Valent buys out Chevron's interest in joint venture
1993	American Cyanamid buys Shell International ag business
1993	AgrEvo formed from Hoechst-Roessel and Schering ag business
1993	ICI forms Zeneca Ag Products
1994	American Home Products buys American Cyanamid
1996	Ciba-Geigy and Sandoz Crop Protection merge to form Novartis
1996	Novartis buys Merck Crop Protection
1997	Dow buys Eli Lilly's share of Dow Elanco, forming Dow AgroSciences
1998	Zeneca acquires ISK BioSciences ag businesses outside Asia
1998	Hoechst and Rhône-Poulenc proposed merger to form Aventis Agriculture
1999	Novartis and Zeneca proposed merger to form Syngenta

through normal obsolescence or suddenly, through government mandates, remains to be seen.

The desire to capitalize on new opportunities and yet at the same time to offset rising costs and compete more effectively on a global scale has precipitated a transformation in the agrochemical industry. The clear and ever accelerating trend among agrochemical companies is towards consolidation, with takeovers, mergers and joint ventures becoming commonplace. Table 2 lists the major consolidation events of agrochemical companies over the past 12 years. Novartis, the largest company in the group with sales 1.5 times greater than its nearest competitor Monsanto, was formed in March 1996 when Ciba-Geigy merged with Sandoz in a transaction valued at $30.1 billion. The 5th largest company, AgrEvo, was created by bringing together the agrochemical businesses of Hoechst and Schering. The 8th largest company, DowElanco, now known as Dow AgroSciences, was created by Dow's acquisition of Eli Lilly's agrochemical business. One of the dramatic moves of 1998 was the announcement by American Home Products (whose American Cyanamid business was the 9th ranked agrochemical company in 1996) of its intention to purchase Monsanto (the 2nd ranked company in 1996) for $34.4 billion.[8] The consolidation of Monsanto with American Home Products' existing agrochemical business would have created the largest agrochemical company in the industry, with combined crop protection sales exceeding $5 billion, but the transaction ultimately failed when highly publicized negotiations between leaders of the respective companies collapsed. Another bold move in 1998 was the announced merger between Hoechst and Rhône-Poulenc to form a new company, Aventis. Aventis Agriculture will consist of three divisions: Crop Science, Animal Nutrition and Animal Health. Crop Science will include Hoechst/Schering's AgrEvo and Rhône-Poulenc's Agro former divisions with nominal annual revenues of about $4.5 billion. At the time of this writing, the most recent move towards consolidation is the agreement between Novartis and AstaZeneca to merge their agricultural divisions forming yet another new company, Syngenta AG. If the proposed merger is approved by antitrust regulators and shareholders, Syngenta will become the world's largest agribusiness, ranking first in crop protection and third in seeds, with combined 1998 revenues of approximately $7.9 billion. The trend toward consolidation can be expected to continue for the foreseeable future, as companies seek partnerships that will help them reduce costs, find marketing synergies between product portfolios, and accelerate the pace of discovering and developing new products.

The advent of agricultural biotechnology has triggered even more profound changes, as leading agrochemical companies are faced with new competitive forces due to the presence of genetically engineered crops with resistance to herbicides and pests. In addition, biotechnology has caused some companies to piece together vertically integrated enterprises capable of making broad product offerings and contracting at the farmer level and meeting downstream customer needs throughout the food and feed production, distribution and processing supply chain. The drive is to participate in the food and feed chain from the farmer to downstream users of foods and feeds, or as some have put it, from the farm gate to the dinner plate. To a large extent, this has developed because biotechnology makes it possible to modify crop germplasm in ways that create novel seed products which contain genetic solutions for meeting customer needs throughout the entire food and feed value chain. To speed up the discovery and deployment of useful genes, companies have added new capabilities to their own internal R&D operations and many have also built alliances and/or acquired seed and biotechnology companies. The first wave of genetic solutions to enter the marketplace has included input traits such as herbicide tolerance and insect resistance, as well as output traits such as high oil corn and high solids tomatoes.

Monsanto has been one of the most aggressive leaders in the retooling that is occurring in the agrochemical industry. Over the past two years, Monsanto's investments have totalled approximately $8 billion, according to published reports. Some major seed and technology company acquisitions include Holden's Foundation Seeds, Asgrow, DeKalb Genetics Corporation, Calgene, AgraCetus and Plant Breeding International. Monsanto apparently will not proceed with the acquisition of Delta & Pinelands Company as originally planned. Monsanto has also built a large and complex network of partnerships with biotechnology companies that offers competitive advantages in target-based molecular design, combinatorial chemistry, genomics and molecular genetics. Some of these include Millennium (leading to formation of the Cereon joint venture), Ecogen, ArQule, InCyte, Mendel and KeyGene.

Monsanto also formed a joint venture with Cargill, one of the world's largest processors and distributors of food products.[9] The venture will contract with farmers to grow Monsanto's genetically engineered grain crops and also calls for each partner to contribute $100 million per year for research and development.

DuPont has also invested in seeds and biotech related businesses, with investments of more than $3 billion in 1997 alone.[10] It recently completed the purchase of Pioneer Hi-Bred, the world's largest seed company, by paying $7.7 billion for the remaining 80% it did not own. A joint venture, Optimum Quality Grains LLC, was formed to grow and market value-added feeds. DuPont also purchased Protein Technologies International, the world's largest producer of soy protein isolate for food applications, as well as the food ingredients business of Dalgety, now known as the Cereals Innovation Centre. In addition, DuPont purchased Hybrinova, a leading company in developing hybrid wheat varieties for Europe. DuPont recently completed the sale of its Conoco energy subsidiary, in order to invest in and focus on the company's life sciences based-businesses, which include its agricultural, nutrition and pharmaceutical businesses.

Other leading companies such as Novartis, Zeneca, AgrEvo and Dow AgroSciences are also expanding and strengthening their capabilities and all have interest in seeds and biotech. The likely outcome of this wave of mergers, acquisitions and alliances will be the creation of several major enterprises, with large investments in R&D and world-wide marketing capabilities to meet the food and health care needs of the burgeoning world population.

The impact of biotechnology

Powerful new tools in biotechnology are creating new business opportunities that cross the boundaries between crop inputs and outputs. Companies are using biotechnology to synergistically link competencies in chemistry and genetics to build robust, flexible and responsive technology platforms and create exciting new product offerings. These products are targeted not only at farmers but also at livestock producers, processors and other end users of foods and feeds. Using a broad range of new biotechnology tools, researchers are designing the next generation of crop protection chemicals and genetically engineering crops and biologicals for improved pest control, yield and quality.[11] These tools are already turning crops into factories to produce value-added foods, feeds and industrial use products.

The first genetically engineered crops to have a large presence in the marketplace have been Monsanto's Round-Up®-tolerant soybeans, cotton, canola and corn, as well as their Bt (*Bacillus thuringiensis*) insect-resistant cotton, corn and potatoes. In 1998, projections called for Monsanto's technology to be used on approximately 50 million acres world-wide: 30 million in Round Up Ready® soybeans, 2 million in Round Up Ready® canola, 0.75 million in Round Up Ready® corn, 10 million in YieldGard® corn, 5 million in Round Up Ready®/Bollgard® cotton and 0.05 million in NewLeaf® potatoes.[12] AgrEvo is also rapidly introducing Liberty Link® crops that are engineered to tolerate the company's broad spectrum herbicide glufosinate. Liberty Link® corn was grown on 700,000 acres in 1997 and could achieve 6.5 million acres in 1998.[13] This is impressive progress for such an embryonic field. Projections in the industry call for genetic-based crop protection solutions to account for about 10–20% of the global $45 billion crop protection products business in 2015, with the remainder of the market going 50% to herbicides, 22% to insecticides and 18% to fungicides.[14] However, it is important to note that in some markets, biotechnology-based solutions could dominate in less than ten years. This is especially true for some insect-control markets.[15]

Biotechnology also offers attractive opportunities to increase substantially the yield potential of many important world crops. Most plant physiologists and molecular geneticists agree that increasing the harvest index above the 50% level already achieved in several crops is unlikely, but there is significant room for improvement in the harvest index of many crops that are still below that level. Using modern genetic approaches to understand and modify crop plant architecture could lead to successes that so far have eluded classical plant breeders. Using biotechnology to elevate hybrid seed production to commercially feasible levels in crops where that has not yet been achieved by classical means is another approach for enhancing yields. In most crop species, F1 hybrids are much more robust than inbred varieties, showing greater resistance to pests and stresses of all kinds, and generally yielding 10–20% more than inbreds. Through genetic engineering, commercially efficient hybridization could be achieved in crops such as wheat and rice by improving mating properties and male sterility systems.

Biotechnology also promises to change the very nature of foods and livestock feeds. DuPont has led the way in commercializing grain products with improved oil and protein characteristics. These products are now being sold by DuPont through its subsidiary, Optimum Quality Grains, L.L.C. Optimum® High Oil Corn (HOC), first commercialized in the early 1990s, contains 7–8% oil versus the 4% typical of unimproved varieties. This boost in oil reduces feed costs by eliminating the need to add fat to the feed ration. HOC was grown on nearly 2 million acres in 1998. Over the next few years, these HOC varieties will also include other value-adding traits, such as increased oleic acid content and high available phosphorus. In soybeans, Optimum Quality Grains is also selling products with improved oil quality. Using genetic technology to block the conversion of oleic acid (a mono-unsaturated fatty acid) to linoleic acid (a di-unsaturated fatty acid) results in a soy oil that contains more than 80% oleic acid versus standard levels of approximately 24%. The benefits of high oleic soy oil include high temperature stability for cooking, health improvements (reduced saturated fat, no *trans* fatty acids from hydrogenation) and reduced processing costs by eliminating the need for hydrogenation. Other value-adding traits such as high available phosphorus (*i.e.* reduced levels of phytic acid) will be introduced into the high-oleic lines.

Many of the other leading agrochemical companies are working to apply genetic engineering to modify the oil, protein and starch of the major crops for valued-added foods, feeds and industrial use products. Ideas for crop based industrial products range from modified textile fibers to fuels such as alcohol and diesel, industrial lubricants, industrial enzymes, modified secondary compounds (sterols, carotenoids, *etc*.), polymer intermediates and novel polymers. It is safe to say that biotechnology is leading a revolution in agriculture that will bring fundamental changes in the way crops are grown, how they are distributed and processed, and how they are used.[16] However, the current debate that has been intensifying, especially in Europe, over the safety and the need for labelling of GMO-based products could severely slow this biotechnology revolution.

Retooling the research engine

In 1996, the 10 largest agrochemical companies reported aggregate R&D expenses of slightly over $2 billion, which represents approximately 10% of sales and 80% of total R&D spending in the industry.[17] These are substantial commitments in a slow-growth business and probably understate the actual R&D investment that is now going on. The level of R&D spending reflects the growing recognition that survival in crop protection depends on building more robust competencies for the discovery and optimization of new development candidates. It also reflects a belief that future growth depends on effectively integrating biotechnology with chemical and genetic discovery programs. Agricultural research is becoming highly interdisciplinary, requiring close co-operation between chemists, biologists, biochemists, molecular geneticists, plant breeders, information scientists, and engineers. Few companies have all the necessary expertise internally, accounting for the need to build partnerships and alliances between companies and/or academic co-operators.

The success of future agricultural enterprises critically depends on retooling the chemical and genetic research competencies that drive new product discovery. Today, some companies are routinely screening 100,000 compounds per year with a goal of screening a million or more in the near future. To accomplish this, the industry has focused on miniaturizing and automating lead discovery screens, with the goal of increasing speed and sample number as well as reducing cost and the amount of compound required. *In-vivo* screens based on natural pest organisms are preferred because of their relevance to the marketplace and their ability to predict utility. However, considerations of compound requirements and throughput rates, combined with advances in the identification and production of molecular targets using the tools of biotechnology, have promoted the use of *in-vitro* screens. The potential of such screens to replace partially or completely whole organism screens is likely to be seriously tested over the next few years.

New information management systems are required for ultra-high throughput screens, for evaluating and recording results and extracting the information necessary to make decisions on whether to advance particular compounds. For chemical synthesis units, the key is to effectively utilize cutting edge combinatorial chemistry technologies to generate large, diverse compound libraries. This requires sophisticated data management and tracking systems. Information technology (including chemoinformatics and molecular design) also plays a critical role in guiding decisions on the acquisition of the large number of chemical libraries that are becoming increasingly available for purchase from outside vendors.

The genetics research competency can broadly be considered to consist of gene discovery, gene delivery (transformation), trait evaluation, and variety development and breeding. Meeting the gene discovery challenge in a timely fashion is critically important to gain competitive advantage. The pace of gene discovery research is already fast, but it is accelerating with each new advance in structural and functional genomics. Here again, automation, information technology and highly skilled people are playing critical roles in driving progress, facilitating the development of new tools for determining DNA sequences, for analyzing and extracting information from changes in gene expression, and for analyzing proteins. Advances in the efficiency of transformation are critically needed as well as rapid, miniaturized methods for evaluating transgenic organisms for desirable traits. Also needed are novel approaches to breeding that will permit the more rapid development of hybrids and elite varieties.

As genetic solutions to crop protection become more of a reality, companies will have to strike the appropriate balance between chemical and genetic approaches to achieve a particular market objective. Co-ordinating genetics with chemical discovery already holds significant promise for maximizing the value of herbicide leads because of the potential for developing crop tolerance via genetic strategies. Companies that succeed in rapidly discovering the site and mode of action for new herbicide leads, as well as in developing systems for rapid discovery and testing of genes for herbicide tolerance, will have the potential to exploit engineered herbicide tolerance. Having access to competitive germplasm will become increasingly important to execute such strategies.

Outlook – technical evolution or revolution

Fortunately, science and technology are continuously producing new waves of technical innovation. Companies with the vision to recognize such waves early, invest appropriately, and ride them have the best chance of long-term success. Transforming or reinventing a company is often associated with riding these new waves of technical innovation.

During the first wave in crop protection, the fields of chemistry and genetics remained somewhat separate (Figure 1). The agrochemical industry relied on chemistry to create new crop protection tools while seed companies relied on genetics to create new, higher yielding varieties. Both industries rode this first wave for more than 50 years by first using empirical approaches and then slowly evolving to the knowledge-based approach of the recent past.

Over the last decade the fields of chemistry and genetics have rapidly converged, largely catalyzed by biotechnology.

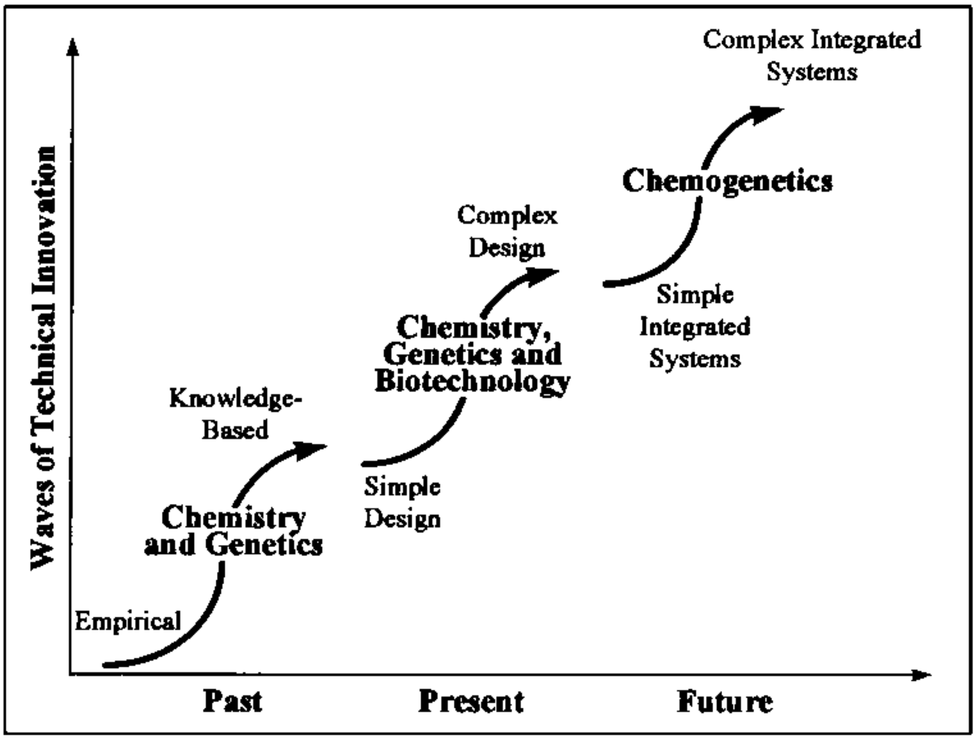

Figure 1. **Waves of technical innovation**

In part, this convergence occurred because the tools of biotechnology are extremely useful for solving both chemical and genetic-based problems. Biotechnology allows one field to complement the other, as in developing herbicide-tolerant crops, where a chemical solution is enabled by biotechnology and genetics. This second wave of technical innovation is attracting the interest and attention of most of the major agrochemical companies. It is this current wave that is shifting existing paradigms and promises to transform companies and the entire agrobusiness food and feed chains. Whole new technology portfolios are now being developed for moving from simple to much more complex design strategies. Today, biotechnologists are creating transgenic crops by incorporating single gene traits and chemists are optimizing chemicals one attribute at a time. As we move up this second wave, technologies for simultaneously solving multiple, complex design problems will be much more commonplace. Combinatorial approaches and informatics will play a key role in achieving these goals.

The future, or the third wave of technical innovation, involves chemogenetics, the true marriage of chemistry and genetics, to yield highly sophisticated, integrated systems. Here crops are engineered with a host of value-added agronomic, grain quality and industrial traits in such a way that these genes can be turned on or off by chemical switches. These chemicals will be applied to crops to turn on the appropriate gene, at the right time and in the right place, to maximise the overall value of the crop. Thus, changes in protein, oil and carbohydrate composition for food, feed and industrial uses could be regulated through this approach, depending on the need and market value. Simple integrated systems involving a chemical switch for single gene traits are already under development. This highlights an important point: as we move from one wave to the next, the timeframes are compressed and the speed of innovation accelerates. This can be seen throughout history and is already being observed today as chemogenetic product concepts are quickly moving from the drawing board to early prototypes.

Will biotechnology bring about a slow, steady evolution or a rapid revolution in agriculture? While the answer to this question will unfold over the next decade, it is the opinion of the authors that if the public accepts this technology through the appropriate regulatory framework, then a revolution is sure to occur. Such a revolution is surely needed if we are to meet the challenge of increasing Earth's carrying capacity to 8.5 billion people by 2040 without serious food shortages and environmental consequences.

Acknowledgements

The authors wish to thank R.T. Giaquinta, B.J. Mazur and R. Bellina for a critical reading and S. Fusca for typing.

References

1. Seckler, D.; Cox, G. "Population Projections by the United Nations and the World Bank: Zero Growth in 40 Years", Winrock Institute, Arlington, 1994.
2. Burns, G.; *et al.* "The New Economics of Food," *Business Week*, May 20, 1996.
3. Brown, L. R., "Struggling to Raise Cropland Productivity" in State of the World 1998, W.W. Norton & Co., New York, 1998, p. 79.
4. Welch, R. M.; Combs, G. F.; Jr.; Duxbury, J. M. "Toward a 'Greener' Revolution". *Issues* **19**, 50.
5. Avery, D. T. "Saving the Planet with Pesticides and Plastic", Hudson Institute, Indianapolis, 1995, Chapter 2, p. 29.
6. Phillips, M. *et al.* "1997 Trading Outcome and Short-Term Outlook," Wood Mackenzie Consultants Ltd., *Agrochemical Monitor* **148**, 3.
7. "UK Reviews OPs (organophosphates) and carbamates," *Agrow News Service*, May 19,1998.

8. Morrow, D. J. "American Home Products Buying Monsanto for $34.4 Billion," *New York Times* June 2, 1998, p. D 1.
9. "Monsanto/Cargill form feed and grain joint venture," *Agrow News Service*, May 20, 1998.
10. Kilman, S.; Warren, S., "Old Rivals Fight for New Turf - Biotech Crops," *Wall Street Journal*, May 27, 1998, p. B 1.
11. For further reading see the series of articles "Plant Biotechnology, Food & Feed" in *Science*, 16 July 1999, **285**(5426), as well as "Resistance to diseases and insects in transgenic plants: progress and applications to agriculture", Shah, D. M.; Rommens, C. M. T.; Beachy, R. N. *Trends in Biotechnology*, 1995, **13**(9), 362-368.
12. Ag Biotech/Seed, "Findings from the Agrobusiness Technology Tour," *Natwest Securities*, August 20, 1997.
13. *op cit*, note 14.
14. A. E. Lund, personal communication.
15. Thayer, A. M. "Betting the Transgenic Farm," *C&E News* April 28, 1997, p. 15.
16. "Plant/Crop-Based Renewable Resources 2020, A Vision to Enhance U. S. Economic Security through Renewable Plant/Crop-Based Resource Use," US Department of Energy, GO-10097-385, September 1997.
17. McDougall, J.; Mathisen, F. "Agrochemical Service: Update of Companies Section," Wood Mackenzie Consultants Ltd., London, November 1997, p 4.

Dr. Elmo Beyer is Vice President, Strategic R&D Planning within DuPont's Agriculture and Nutrition businesses. He has responsibility for strategic planning related to new genetic- and chemical-based technologies. With the recent merger of Pioneer Hi-Bred International, Inc., these responsibilities span the seeds, foods, feeds, biomaterials and crop protection markets. Dr. Beyer serves on DuPont's Corporate Technology Council and the Agricultural Enterprise Strategic Steering Team. His leadership in science and technology at DuPont has helped elevate the Company to a position of global leadership in agricultural biotechnology and chemistry. Dr. Beyer joined DuPont in 1970 after receiving a Ph.D. in Plant Biochemistry from Texas A&M University.

Dr. Forrest Chumley is Manager, Biotechnology Partnerships & Alliances in the DuPont Agricultural Enterprise. He is responsible for meeting key technology access needs by facilitating collaboration with academics and industrial partners. Dr. Chumley joined DuPont in 1985, after completing a Ph.D. in Molecular Biology at the University of California and a postdoctoral fellowship at Cornell and M.I.T.