Biology, Innovation and the Fertilizer Industry- Is the Change Imperative?

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The fertilizer industry is undergoing dramatic change. And the industry must change because the way we serve our customers, sociopolitical trends, the impact of new technologies and the advent of free trade and a global market place leave us no choice. The change imperative is very strong.

FORCES DRIVING CHANGE

Better Serving the Farm Customer

Today's customer is more technically literate, educated and demanding. In developed agriculture countries, the farmer is as much a businessman as an agronomist and his business is supported by easy access to integrated information systems.

Our technical problems are increasingly challenging. No one product or process will solve the problems so integration of technology is critical. Data collection, integration, interpretation and dissemination requirements will be extensive.

Sociopolitical Trends

There are a number of sociopolitical trends which will also affect the fertilizer business.

Government regulations are contradictory. There is a strategic political and business desire to reduce government regulation, to streamline the system. This is counterbalanced by a need to ensure a safe and healthy environment.

Thus there will be a continued focus on stewardship of the environment and safety. But these initiatives should be led by industry to avoid government regulations. An example is the "Responsible Care" initiative led by the chemical industry.

There will be increased pressure to reduce the use of chemicals or at least improve the efficacy of the active ingredients. Concerns about the negative effects of chemical use (chemophobia) are real and will result in a trend to increase the use of biologicals to control crop diseases and stimulate plant growth.

Although the public and the press have become increasingly aware of the impact of science on their lives, much more work is required to ensure scientific literacy. Equally as important, the public needs to understand how to evaluate risk.

The Challenge to the Fertilizer Industry

Fertilizer Use Efficiency (FUE), as determined by stable radioisotope techniques, clearly shows that the uptake of applied fertilizer nutrients by plants is unacceptably low. Depending on the nutrient source and application method, FUE of nitrogen is often less than 50 per cent, phosphorus less than 20 per cent and sulphur can be less than 10 per cent. Although there are many chemical and biological reasons why fertilizers are not taken up efficiently by the plant (immobilization, leaching, denitrification, volatilization, distance to the seed or the roots, etc), what other industry would tolerate such a low product efficiency?

With this knowledge of low FUE, what is our industry doing to develop better fertilizers and to improve the value of our products and services for our farm customers?

The IFA/FAO Agriculture Conference held in Rome in March 2003 recognized that, as an industry, we have not had a significant history of research and development or innovation. Unlike our sister industries, the crop protection and seed industries, we have not extensively harnessed fundamental research and development (R&D) to develop better fertilizer products or to substantially improve our production processes.

The consequences of fertilizer misuse are coming back to haunt us. The potential for legislated restriction on the use and application rates of fertilizers can be blamed on subsidies but, in reality, it should be largely avoidable with our current agronomic knowledge base.

And, we are a chemical industry. No chemical industry has ever been favourably viewed by the public.

The Fertilizer Industry’s Competitive Environment

The competitive environment of the fertilizer industry is also changing. In the crop protection industry, rationalization through acquisitions and mergers has led to a few players who are capable of managing world-scale businesses to compete in a global economy. In contrast, some of the largest global nitrogen fertilizer companies constitute less than 5 per cent of the global market demand.

Crop protection companies compete on the basis of new products and new markets. They have realized that innovation and creativity are often stifled in larger corporations. Instead they have created partnerships with "biotech boutiques." The partnership starts with small investments, perhaps contractual work, but soon grows to a point where the multinational takes an equity position in the smaller company. At the appropriate time, once the risk of the fundamental research has passed, the multinationals "cherry pick," that is, they acquire the biotech boutiques and bring them in-house to create a proprietary strategic advantage.

There is a strong trend to having more R&D in industry. One of the main drivers is the reduced funding government agencies are giving to university and government research facilities. This reduced funding has the positive effect of encouraging more collaboration between the industrial, government and academic sectors. However, this cooperation is driven primarily by financial exigency rather than by a strategic plan to link the three sectors to better serve the taxpayer.

This lack of support by government for fundamental research and the renewed emphasis on "results" by funding agencies creates a short-term focus that could have serious long-term negative implications on our future ability to compete globally.

Non-Traditional Competitors

There will continue to be quantum leaps in technology which will give strategic competitive advantage to those who can capture the benefits. The fertilizer industry is seeing the advent of non-traditional competitors. This is both because of the international nature of the business, but also because the crop protection, seed and biotech companies see opportunities in plant nutrient optimization.

Most of these new challengers are focusing on biological products which enhance root health, either by controlling root diseases or by hormonally stimulating root growth. Fundamentally, a larger, healthier root, will assimilate more nutrients and moisture and this should translate into higher yields.

Three examples of non-traditional competitors are Dow AgroSciences and Uniroyal/Gustafson. Dow AgroSciences marketed the P-solubilizing fungus *Penicillum bilaii* under the trade name "Provide." Philom Bios now successfully markets *P. bilaii* with rhizobial inoculants (Tag Team^{TM}) or alone (Jump Start^{TM}) for annual grain legumes in western Canada. All of these products are registered under Canada's Fertilizers Act. Gustafson commercializes a root stimulating bacterium for cotton under the trade name "Kodiak."

CHALLENGES AND OPPORTUNITIES TO THE FERTILIZER BUSINESS

The Continued Improvement of Crop Yielding Potential

Conventional plant breeding has dramatically increased the yield potential of crop varieties over the 20th century. More recently, many new plant genetic technologies have been added to the set of tools available to plant breeders. These tools will result, among others, in plants with new agronomic characteristics ("input traits") for higher yields and, thus, higher nutrient requiring crop varieties.

For instance, induced resistance to lepidopterian larvae (e.g. corn borer) using Bt genes, results in healthier plants that need more nutrients. Herbicide tolerance (HT) extends the rotation of higher nutrient requiring crops. In 2002, Bt and/or HT varieties were grown on 58.7 Mha according to the ISAAA.

In addition, crops with improved nutritional or processing characteristics ("output traits") are being created. Specialty oils, proteins or even utilizing crops to mass produce pharmaceuticals will result in crops with unique nutrient input requirements. Calgene's new lauric acid flax has changed that crop from an industrial oil source to a potential competitor with palm oil as an edible oil source.

The last quantum leap in per unit fertilizer consumption was due to the introduction of hybrid corn and sorghum. Self-pollinated cereals have been very difficult to create as hybrids. However, research has broken that technology barrier in rice and, more recently, in wheat.

One area where the outcome of plant genetics has not yet been commercialized relates to the plant's ability to assimilate nutrients and moisture. Better understanding and using this mechanism will extend our potential to grow crops in new geographies as plants are bred for higher tolerance to drought, salinity, acid soils and temperature extremes.

Generally speaking, whether the technology is plant genetics, soil conservation, machinery or precision farming, increased yield potential automatically translates into higher nutrient demand.

(increased yield = higher nutrient demand)

New Crop Traits with Potential Impact on Fertilizer Consumption

- *Enhanced potassium absorption*

  The gene(s) that control potassium (K) absorption have been isolated and cloned. These genes could be manipulated to enhance the ability of crops to assimilate potassium.

  A negative impact on K fertilizer consumption could be expected during the few years after adoption of the varieties containing this trait, since these varieties would be able to better use the soil K which is hardly available to plants. The impact on K fertilizer consumption should then be neutral, since there will be a continuous need to compensate K exports.

- *Higher bioavailable phosphorus content*

Phytase expressing maize, with higher levels of bioavailable phosphorus, is being developed to feed pigs and poultry. With these varieties, there would be no need to supplement diets with feed phosphate. Also, phosphorus losses to the environment would be reduced through use of such varieties. Similar work is being done also on soybean, rapeseed and alfalfa.

The first varieties with this trait are expected to be commercially released in 2003.

A quite significant market loss could be expected for those phosphate fertilizer companies providing feed grade phosphate. On the contrary, this innovation should have a limited to medium positive impact on fertilizer P use, as manure from animals fed with low phytate grain should have much lower P levels. Lower P content in manure should be compensated by higher use of manufactured fertilizer P.

- *Improved protein content*

Maize with increased protein content, aimed at improving the nutritional value of maize in animal feeding, is under development. These maize varieties could lead to lower requirements in soybean meal to supplement animal feed.

The first varieties with this characteristic should be available around 2005.

These varieties are expected to lead to higher fertilizer N use to compensate higher nitrogen exports to produce more proteins. Provided the quality of proteins in maize could be improved to the extent that maize protein would be a substitute for soybean protein, such varieties could also lead to a shift from soybean to maize, a crop with higher fertilizer requirements.

- *Improved content in essential amino acids*

Another significant development in maize breeding is the development of varieties with increased lysine and methionine contents, two essential amino acids that are often limiting factors in low protein diets. These varieties would provide a much more balanced diet, in particular for pigs and poultry. Requirements in essential amino acids could be met through lower protein diets.

These varieties are close to commercialization.

From a fertilizer consumption standpoint, these developments should lead to:

- A medium increase in fertilizer S, necessary to compensate for sulphur exported in additional methionine produced by the crop;
- A possible limited reduction in fertilizer N, because lower protein diets would be necessary.

Researchers are trying to combine higher contents in essential amino acids with higher protein content. Such varieties would have a positive impact on fertilizer S and probably a neutral one on fertilizer N.

- *Higher iron content*

Micronutrient deficiencies in general, and iron deficiencies in particular, are among the major health concerns today. According to the United Nations, two billion people suffer from severe iron deficiencies alone. Work at the genetic level is being done on some staple food crops to compensate for these deficiencies through higher micronutrient uptake and/or storage in edible parts, or better bioavailability of the nutrients.

"Golden Rice", a rice with higher vitamin A and iron content, is expected to be available to farmers within a few years, probably around 2005.

A quite significant positive impact on iron use can be expected, since higher iron exports by the crop would, *a priori,* require higher iron fertilizer deliveries.

- *Other functional foods, nutraceuticals*

In addition to crops with higher iron content, several plants and food products with different nutritional composition are being developed. This includes, for instance, plants with higher vitamin content, modified fatty acid profiles, increased levels of beneficial molecules such as lycopene or isoflavones. These so-called "functional foods" or "nutraceuticals" will probably require adapted fertilization schemes for full expression of the new trait. Moreover, tailored "identity preserved" management practices will probably be required by the food or pharmaceutical industries for these varieties aimed at providing raw material for high added value markets.

Many of these "output" traits should be available soon.

From a fertilizer use standpoint, these varieties would require more balanced nutrition and, therefore, probably higher consumption of potassium, sulphur and micronutrients.

- *Tolerance to drought and salinity*

Work on tolerance to drought and salinity is ongoing for several crops through, for instance, the introduction of genes leading to mannitol production by plants, or increasing acquisition and storage of potassium vs. sodium.

Commercialization of salt tolerant tomatoes (one of the most advanced crops in this respect) could start around 2005.

In fertilizer terms, higher potential yields in areas with water deficits or saline soils would require more nutrients and, therefore, this is expected to generate an increase in fertilizer use. Moreover, salt tolerant varieties would probably need more fertilizer K to fully express the new characteristic.

- *Aluminium tolerance*

  It is estimated that approximately 40 per cent of the tropical soils are acid soils, associated with problems of aluminium toxicity and, to a lesser extent, manganese toxicity (in addition to critical problems of low phosphorus availability). This leads to severe yield potential reduction. In order to overcome this major constraint, research work is being carried out to develop aluminium tolerant plants.

  Varieties expressing this trait might be available to the farmers by the end of the decade.

  This development will probably lead to significant growth in fertilizer consumption in tropical areas to compensate higher nutrient exports associated with higher yields.

- *Phytase-excreting plants*

  A large proportion of organic soil phosphorus is phytate, a form that is hardly available to plants. This problem could be at least partly alleviated through the development and cultivation of phytase-excreting plants.

  Several years of development and field trials are still required before commercial release of such varieties, but they should be available to farmers before 2010.

  A quite significant negative impact on fertilizer P consumption could be expected during at least the few years after adoption of the varieties with the new trait, since these varieties would be able to use previously immobilized phosphorus. Then, fertilizer P use should stabilize at a level aimed at compensating P exports.

- *Improved nutrient uptake and metabolism efficiency*

  Studies of the plant genomes of rice, maize and model dicots such as *Arabidopsis*, has allowed the identification of genes and gene variants improving nutrient uptake and metabolism efficiency. Use of marker assisted breeding to breed varieties with such genes would greatly improve nutrient use efficiency, in particular for nitrogen and phosphorus, thus allowing using less fertilizer for the same crop output and less losses to the environment. However, progress in this area might be limited since there is a close link between the harvest index (long used by conventional plant breeders to enhance crop yield potential) and nitrogen use efficiency and, therefore, latitude for improving nitrogen use efficiency in major crops might be limited. Potential for improving phosphorus use efficiency might be higher *a priori*.

Once genes are associated with a function, progress might be relatively fast through the use of marker-assisted breeding. However, as mentioned earlier, the challenge would be to get optimum expression of the selected gene(s) in an improved genetic background grown in a specific environment. This will likely require some more years of genomic research, and varieties with improved nutrient use efficiency traits might be commercially available around 2010.

It is worth noting that varieties generated by marker-assisted breeding would not be transgenic and, therefore, would not require several-year trials to comply with biosafety and food/feed safety procedures. Moreover, their development would not be subject to the current consumer suspicion against transgenic crops in Europe.

These traits should lead to a medium reduction in fertilizer N and P consumption, since lower fertilizer use would be required to obtain the same crop output. Some researchers claim that efficiency could be increased by up to 20 per cent, but this information has to be confirmed. Moreover, it is not clear how a 20 per cent increase in nitrogen use efficiency would translate into nitrogen fertilizer consumption? The impact would probably be different whether the increase is at the uptake, storage, transport or metabolism level.

- *Genetic control of heavy metals uptake and/or tolerance*

Genetic control of heavy metals uptake and/or tolerance could be used two ways: (i) in decreasing uptake by food crops and (ii) in increasing tolerance and uptake by plants that would be used for soil bioremediation purposes. Current work focuses mainly on arsenic, but similar work could be done on cadmium and other heavy metals. Use of genetic control could be an alternative to burdensome and sometimes unjustified regulations on heavy metals contained in some fertilizers, such as on cadmium in phosphate fertilizers, or on arsenic and lead in micronutrient fertilizers.

Varieties with these traits could possibly be available around 2010. It should be noted that in the USA and Canada, varieties of wheat, flax and sunflower with low cadmium uptake are being screened and developed through conventional breeding.

The impact of these traits would not be on the total fertilizer consumption level, but on the origin of the fertilizers used. This could avoid a ban on certain fertilizer sources having above average contents in heavy metals.

- *Improved energy efficiency of energy crops*

  Production of biofuels from crops requires a several-step industrial process. Transformation of maize so that it produces its own amylase would simplify the industrial process to use maize for producing ethanol. This development would not require the breakdown of starch into sugar, and would make biofuels more competitive vs. fossil fuels.

  The time required before the commercial release of such varieties is uncertain. But since genetic control of this trait is simple, it should be available around 2010.

  From a fertilizer demand point of view, making biofuels more competitive would lead to an increase in global crop production. This would require significantly more fertilizers, provided the policy framework is also supportive of biofuels.

- *Low lignin*

  In order to make forestry a more profitable business, researchers are developing low-lignin fast-growing trees. These trees would greatly benefit the pulp and paper industries, with lower energy requirements for paper production, and reduction in waste production. These developments would also contribute to the preservation of wild forests.

  With respect to the long growing cycle of forest trees, it is quite unlikely that this innovation will be released before 2015.

  As far as fertilizers are concerned, it can be forecast that more intensive forest management would probably require the use of fertilizers to compensate the resulting higher nutrient exports.

- *C4 genes*

  Cereals are split into two groups depending on their photosynthesis efficiency: the C3 group (wheat, rice) and the C4 group (maize), the latter being much more efficient. Therefore, transferring C4 genes from maize to rice or wheat would improve their photosynthetic efficiency. Such work is being done on rice in Japan and at the International Rice Research Institute (IRRI), and it is claimed that this could increase rice yield potential by 20 per cent.

Since the photosynthesis mechanism involves many genes, it is quite unlikely that this trait would be transferred to C3 plant species before the next 10 to 20 years.

Higher potential yields generated by this transformation would result, of course, in higher nutrient requirements.

Improvement of Microorganisms and Symbiosis

- *Phosphorus solubilization*

A phosphorus-solubilizing fungus (*Penicillium bilaii*) is used either alone (Jump Start™) or with rhizobial inoculants (Tag Team™) to stimulate phosphate uptake.

P. bilaii is currently used in western Canadian and some northern US soils.

An impact similar to the one expected with phytase-excreting plants is obtained.

- *Sulphur oxidization*

There is a strong desire to have higher analysis S fertilizers but elemental S is not readily plant available. Researchers at the University of Saskatchewan and Leeds University in the UK have isolated a sulphur-oxidizing bacterium which efficiently oxidize elemental sulphur.

The use of sulphur-oxidizing bacteria would facilitate the use of elemental sulphur versus oxidized forms of sulphur in fertilizers.

- *Ability to develop symbiosis with nitrogen fixing bacteria*

Interactions between *Rhizobia* and legumes are very complex. Collaborative research between Chinese and Australian scientists has created legume-like nodules on wheat although nitrogenase expression was not achieved.

The Nod factors are one of the signaling molecules involved in this symbiotic interaction. The Nod factors are synthesized by the *Rhizobia*, and at least six plant genes playing a role in Nod factor perception and transduction have been identified in legumes. Two teams, in the United Kingdom and Hungary, have recently identified one of these six genes. Various other teams are now trying to identify the other five genes. In addition, other rhizobial signals are involved in the symbiotic interaction and a number of plant genes are expected to be required for their perception, transduction and the induction of the symbiotic response. Thus, transcriptomic approaches on the model legumes have identified a number of additional nodule-specific genes.

Genetic control of the symbiosis ability involves several interactions between crop genes and rhizobial genes. Therefore, in the absence of further information, it is probably quite safe to say that this trait should not be available in cereals before 2020, and probably much later. Moreover, its possible transfer to cereals remains questionable and still hypothetical, as no "proof of concept" has yet demonstrated that the transfer of nitrogen fixing ability to non-legumes is possible. Furthermore, if such a transfer would be feasible, how would these genes interact with the other cereal genes and, therefore, how would the symbiotic trait be expressed in cereals? Not enough information is available yet to answer this question and the many others mentioned in section 4 of this paper.

This development could potentially lead to catastrophic impacts on the nitrogen fertilizer industry since, theoretically, crops that would be transformed would not need any more fertilizer N. Of course, the likely impact would be much less detrimental for a number of agronomic and economic reasons.

Some Developments in Other Technologies

- *Conservation farming*

  The trend towards minimum and zero tillage is enhancing the phosphorus supplying power of many soils. Vesicular arbuscular mycorrhizae (VAM) better solubilize unavailable soil P when soils are not tilled. Tillage rips apart the fungal hyphae thus reducing their ability to make soil P more available.

  From a fertilizer demand stand point, conservation farming has or might have a limited negative impact on fertilizer P through better phosphorus availability.

- *Seed coating with phosphorus*

  Coating seeds with phosphorus improves the efficiency of the plant nutrient, which is located close to the roots right after germination.

  This product (iSeed ™) was commercialized in 2003 for the first time. It was marketed in Northern Europe on cereals and rapeseed.

  Potentially, this technology allows using less P fertilizer for the same crop output.

- British scientists at the John Innes Institute at the University of East Anglia, Norwich have successfully reduced atmospheric nitrogen (N_2) at standard temperature and pressure and are proposing that small solar-powered urea plants using unique transitional metal chemistries may provide urea fertilizer in the future.

This technology would allow producing N fertilizer closer to the place of consumption and, thus, reducing transportation costs.

CONCLUSION

Today, many inventions with a potential direct or indirect impact on crop nutrition are being developed. Although most of these technologies will not be marketable within the next few years, it is critical that we are aware of these emerging and potentially disruptive technologies. Their impact on fertilizer demand might be either positive or negative, depending on the invention. A rough preliminary assessment shows that, in a 15-year timeframe, positive impacts on fertilizer demand might be slightly more significant than the negative ones, and that this trend might reverse in a 15 to 30-year timeframe. However, this forecast requires continuous monitoring of future developments, since the pace of release of biotechnological inventions is expected to speed up with our improved understanding of the crop genome.

There will be challenges for the fertilizer industry. These challenges will remain unless we lead and capture these new technologies. The shift from fertilizer to plant nutrient supplier gives us the opportunity to lead by developing disruptive technologies before non-traditional competitors do.

Our industry must lobby governments to ensure that they understand the impact of fundamental R&D on our ability to feed a hungry world. As an industry, we cannot accept the continued erosion of quality in our universities and government laboratories due to reduced public financial support.

Lastly, we must recognize that our ultimate customer is neither the fertilizer dealer, nor the farmer, but the growing crop. Our ability to supply an integrated crop production package to ensure healthy crop growth will bring benefits through the entire value chain.