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The food chain: Plants, animals and man
Plenary Lecture

Engineering plants for animal feed for improved nutritional value

Peter E. V. Williams
Syngenta Crop Protection AG, WRO-1002.13.63, Schwarzwaldallee 215, CH-4058 Basel, Switzerland

Feed formulation to meet nutritional requirements of livestock is becoming increasingly challenging. Regulations have banned the use of traditional high-quality protein supplements such as meat-and-bone meal, pollution from animal excreta of N and P is an issue and antibiotics are no longer available as insurance against the impact of enteric infection and feed anti-nutritional factors. The improved genetic potential of livestock is increasing daily requirement for energy and protein (essential amino acids). To benefit from the enhanced growth potential of livestock diets with high nutrient density are needed that can be formulated from crops without increased cost. Genetic modification of commodity crops used to manufacture animal feed in order to improve the density and quality of available nutrients is a potential solution to some of these problems. Furthermore, crops may be used as biofactories to produce molecules and products used in animal feed with considerable reductions in manufacturing fixed costs. Nevertheless, there are considerable not insurmountable challenges, such as the creation of sufficient economic value to deliver benefit to all members in the feed production chain, which is an essential element of identity preserving and delivering the technology to livestock producers. Individual output traits in the major commodity crops may not provide sufficient value to adequately compensate all the members of the feed production chain. Successful adoption of output traits may rely on inserting combinations of agronomic input traits with specific quality traits or increasing the value proposition by inserting combinations of output traits.

Feed: Genetic engineering: Genetically-modified crops

Introduction of genetically-modified (GM) crops into the feed and/or food chain is a contentious issue, but the technology has the potential to offer major benefits to animal and human nutrition if it can be proven to be sustainable at no detriment to food safety compared with the use of present crops. Avery (2001) argued that high-yield modern farming employing biotechnology is one means of conserving the natural habitats of the planet. Already the wider benefits of the use of the technology are being reported. The wide adoption in maize of the *Bacillus thuriengensis* (Bt) gene that prevents insect damage from the European corn borer (*Ostrinia nubilalis*) has resulted in less insect damage to the crop and hence reduced development of molds and less contamination with mycotoxins (Pietri & Piva, 2000). Following the development of herbicide resistance in plants, new herbicide management policies have reduced the use of chemical herbicides.

Two classes of the genetic modification of crops need to be defined; these classes relate to either agronomic factors (input traits; IPT) or quality factors (output traits; OPT) associated with the composition of plants. IPT relate to the manipulation of the plant genome to influence agronomic characteristics, and include herbicide resistance, insect tolerance, drought resistance or any factor that specifically relates to the germination and growth characteristics of the plant. OPT relate to the yield–compositional characteristics of the plant. OPT may be further classified into those characteristics that are introduced into plants

Abbreviations: Bt, *Bacillus thuriengensis*; GM, genetically modified; HOC, high-oil maize; IPT, input traits; OPT, output traits.
Corresponding author: Dr Peter E. V. Williams, fax +41 61 323 69 44, email peter.williams@syngenta.com

either when they are to be grown on a broad acreage basis, such as improvements in the energy or protein value of commodity crops, or when they are used as an alternative production system providing large quantities of high value proteins.

The adoption of input traits

The acreage planted to GM crops since 1995 is shown in Fig. 1. The first wave of planting of GM crops has been dominated by plants expressing IPT, either herbicide or insect resistance, or latterly combinations of the two traits. Soyabean (58 %), maize (23 %), cotton (12 %) and rapeseed (7 %) were the four most important crops, and the dominant traits were herbicide tolerance (74 %), insect resistance (19 %) and a combination of herbicide tolerance and insect resistance (7 %; James, 2001). Crops expressing IPT have been tested in a large number of feeding trials and have proved their substantial equivalence in terms of composition and nutritional value with non-GM counterparts (Aumaitre, 2001; Clarke & Ipharranguerre, 2001; Folmer *et al.* 2002). Aumaitre (2001) concluded that there was an absence of any negative effects.

The reluctance of European consumers to accept GM crops, and even produce derived from animals that may have been offered feed containing GM material, is an example of the requirement for identity preservation. There is no difference between a non-GM crop and a crop expressing a specific OPT in the increased cost required for identity preservation when compared with the commodity form. Bennett (2000) reported that feeding non-GM soyabean and maize to UK livestock would cost producers £61×10^6 per year if retailers required non-GM products. The producers most affected would be pig and broiler producers. The EU calculated that keeping non-GM and GM crops separate from the farm gate to the consumer could raise raw material costs by as much as 6–17 %, dependent on the grains and separation systems involved (Farmers Weekly, 2000). This additional cost is an example of the premium that must be paid when any raw material ceases to be a single commodity and a speciality crop needs to be handled in order to identity preserve the value of a trait to the point of sale.

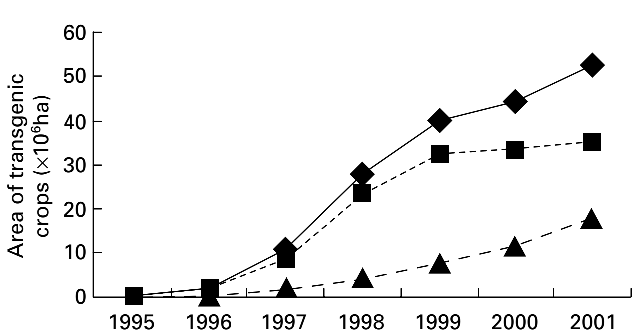

Fig. 1. Global area (◆—◆) of transgenic crops, showing the areas for industrial (■—■) and developing (▲—▲) countries. (Adapted from James, 2001.)

Input traits and the benefits for growers

Crop growers consider three major criteria when deciding on a strategy for planting crops with new agronomic traits. The first is the opportunity to enhance profit on the farm and the second is the reduction in input costs. When genetically-engineered herbicide resistance is incorporated into crops, management is made easier and cheaper for growers, since the number of herbicide applications to the crop is reduced. The third is the ease of incorporation of the new technology into the existing farm operations. The rapid adoption of IPT illustrated in Fig. 1 is in no small way due to the very rapid and quantifiable capture of the value of the trait by the grower.

Bt hybrid seeds are priced at a premium over conventional hybrids. Bt hybrids were selling for a premium of approximately US $12–24 per ha or US $15–30 per unit. On-farm performance of Bt maize indicated that yield increases were in the range of 0·6–1·8 t/ha when compared with conventional non-Bt hybrids. The benefits provided for the grower are closely tied to the value of the maize and are greatly diminished in years of either low European corn borer infestation or low maize prices. Compared with a control using insecticides the net economic profit from the Bt trait can range from at least $20 to 37 per ha.

It is estimated that the increased yield achieved with Roundup Ready soyabeans (Monsanto Corp., St Louis, MO, USA) is of the order of 0·067–0·134 t/ha (Wheat, 1998). This factor plus the savings on herbicides amount to an increase in income of between US $11 per t and US $18 per t, even allowing for the premium payments on the GM seed (Wheat, 1998). Roundup Ready seed is priced so that the farmer is likely to see several dollars in savings per acre.

The requirement for output traits

The last 5 years have seen several paradigm shifts that have considerably affected and altered methods of livestock feed production. There have been severe restrictions on the use of animal meals in the production of livestock feed. Consumer preference has favoured production of livestock products from animals raised on diets devoid of any animal by-products. Under such circumstances it is a problem to identify alternative cheap sources of raw materials with available high energy density and high-biological-value protein that have been supplied traditionally by animal fat and meat-and-bone meal respectively. The problem is exacerbated by the increase in genetic potential of pigs and poultry for lean tissue deposition, thus increasing the need of livestock for high energy density and increased quantities of available amino acids. Energy and protein are commodities traded on the worldwide market. Use of energy resources and the food needs of the human population are in direct competition with the animal feed industry for these commodities. As such their availability and cost will be driven by worldwide supply and demand and, in competition with the human population for high-value energy and protein, the livestock industry will be faced with increasing costs for its basic raw materials. There is, thus, a need to modify the nutrient composition of plants to increase protein and energy content and availability.

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A wide range of potentially-modifiable OPT have been identified, and a comprehensive list based on developments in progress, identified in patent applications, is presented in Table 1. GM plants will offer no interest for animal production unless the new traits will in some way substantially reduce the cost of the feed formulation and the cost benefit must be attainable in all countries involved, in order to avoid delocalisation of systems of animal production.

Output traits and the challenge of value capture

The reasons why growers may adopt OPT (quality traits) are different from those that drive the adoption of IPT. Again, the first and foremost criterion is value capture, second farmers are also keen to be part of any emerging technology and third is risk management, with a desire not to be left behind. For most of, if not all, the quality-trait crops the need for identity preservation, coupled with the current tendency for these crops to experience some yield lag, has resulted in premiums being paid to producers to grow them under contract. Generally, there are three types of costs associated with quality traits: (1) grower premiums and/or incentives; (2) identity preservation costs; (3) end-user costs of adoption.

To be sold in substantial volume a feed quality trait needs to be adopted by at least two end-user segments (poultry, pig, beef, dairy or export). Without broad appeal a quality trait cannot become a major percentage of production. For traits to have broad appeal in the USA they must be expressed in the two major crops: standard maize, of which approximately 72 % is used for feed production; soyabeans, of which 80 % is in some way used in feed production.

Growers are paid premiums or some other form of compensation for the increased risk of growing a quality trait. In the past these premiums have been at the level of US $6.0 per t for waxy maize to a high of US $660 per t for organic clear-hylum soyabeans. The majority of premiums fall in the range US $7.5–20 per t. Typical premiums for speciality grains without any yield lag are

Table 1. Output traits of potential value for feed and food identified from patent applications

Crop	Use	Trait	Improvement
Lucerne*	Feed	Lignin	Improved digestibility and/or low lignin
Barley	Food	Flavour and/or yield	Improved malting quality
Chickpea†	Feed	Amino acid	Increased amino acids (methionine and lysine)
Clover‡	Feed	Amino acid	Increased amino acids (methionine and lysine)
Maize	Feed	Amino acid	High protein with balanced amino acids
	Feed	Mycotoxin	Fumosin detoxifying
	Feed	Oil	High oil content
		Oil and/or amino acids	High oil with increased digestibility
		Oil and/or P	High oil with increased P availability
Rapeseed	Food and/or industrial	Oil	High lauric acid
	Industrial	Oil	High myristate
	Food	Oil	High stearic acid
	Food	Oil	High medium-chain fatty acids
	Industrial	Oil	Speciality lubricant (waxes) jojoba oil
	Food	Oil	High long-chain PUFA
	Food	Oil	High medium-chain fatty acids
	Feed and/or food	Oil	Low saturates and/or high MUFA and/or low PUFA
	Feed	Oil	High oil
Cotton seed	Food	Oil	High oleic acid
Lucerne	Feed	Amino acids	Increased amino acids (methionine and cysteine)
Lupin§	Feed	Amino acids	Increased amino acids
Palm	Industrial and/or food	Oil	
Peas‖	Feed	Amino acids	Increased amino acids (methionine)
Potato	Food	Shelf-life	No browning
Rapeseed	Industrial	Oil	High erucic acid
Soyabean	Food	Oil	High oleic acid, lower saturated fat
	Food	Oil	High stearic acid
	Food	Oil	High palmitic acid
	Food	Oil	Low saturated fat
	Feed and/or food	Protein levels	Increased levels of protein
	Feed	Anti-nut factor	Low stachyose
Sunflower	Food	Oil	High oleic acid
Sorghum	Feed	Carotenoid	High carotene
Tomato	Food	Shelf-life	Increased shelf-life

MUFA, monounsaturated fatty acids; PUFA, polyunsaturated fatty acids.
* (*Medicago sativa*).
† (*Cicer arietinum*).
‡ (*Trifolium* spp.).
§ (*Lupinus* spp.).
‖ (*Pisum sativum*).

expected to be a minimum of approximately US $6.0 per t. There are few speciality crops without some sort of yield lag that would need to be additionally recompensed. Furthermore, growers have no preference as to what trait is inside the crop, unless the trait causes detrimental environmental or food safety effects. Presently, few growers are willing to adopt a monoculture approach with these new crops, and the GM crop tends to represent up to one-third of the entire acreage.

In order to capture the value of an OPT (quality trait) when used as a major component in animal feed, changes and consolidation will be required in the infrastructure of the feed industry. Capture of value from OPT is more complex when compared with IPT, as there are more links in the value chain. For IPT there are typically three links in the chain, the gene engineer, the seed producer and the farmer who grows the crop. The grower, as indicated earlier, captures the value. For OPT it is not the grower that captures the value, and there may be as many as four additional participants in the chain (grain storage, grain treatment, compound-feed producer, livestock producer). In order to achieve a situation in which the nutritional benefit imparted into the crop is transferred to the livestock producer, it is essential that at each stage of the movement and processing each of the participants who contribute in the process can gain economic benefit. It is even more important that none of the participants incur any financial loss or are in any way compromised by handling the crop. The value of the trait engineered into the crop must be capable of being captured and the value of the 'uplift' to the end user must be considerable. The situation differs dramatically according to the number of participants in the value chain and the type of crop concerned.

A recent study (Maltsbarger & Kalaitzandonakes, 2000) has paid particular attention to the hidden costs associated with identity preservation. The findings indicate that differences in local supply conditions and asset configurations at the farm, elevator and processor can produce substantial variation in segregation and identity preservation costs. The study included quantification of the components of segregation costs that could include compositional analysis, additional analytical equipment, single-season expenditures such as an incremental cost in labour for segregation and identity preservation handling and costs of misgrades where identity preserved stock is accidentally stored as commodity. Under-utilised capacity was a major concern for elevator managers considering identity preservation. Three case studies of elevators of differing configuration were carried out which involved segregation of high-oil maize (HOC). The additional costs of segregation were up to US $14 per t, which is considerable. However, the lowest cost of US $6 per t was achieved with an elevator that had a large capacity but split the grain between many storage bins. The reduction in identity preservation cost was achieved through greater flexibility in filling patterns to maximise storage utilisation within the batch-processing identity-preservation system. The most interesting scenario for the smallest elevator was achieved when the entire facility was dedicated to the processing of HOC, but even then it did not achieve the lowest cost per bushel. At the other extreme, the largest facility suffered greatly from under-utilised capacity. This example typifies the problems associated with the handling of what is essentially a range of different raw materials, which is the situation that will exist when maize ceases to be a single commodity. Typical costs for identity preservation of maize and soyabean meal are shown in Table 2. These costs compensate the grower, the distribution system and the processor. However, the technology developer and/or seed supplier and end user have not been rewarded, the end user has only paid for costs incurred. For maize this cost represents a minimum of an additional value of approximately US $10 per t in order to adequately compensate all the participants in the chain, and for soyabean approximately US $28 per t to compensate for the additional participants in the chain.

Soyabean production is a particular case where additional consideration must be given to the value chain. The crushing of the seed to yield the oil is a pivotal process and the profitability of the oil crushing process is critical. Oil and meal are two co-products from the harvesting of soyabeans. The oil is used as a high-value product in human nutrition, with only 5 % for industrial purposes; 97 % of the meal is used for animal feed. However, the prices of the oil and meal are greatly influenced by world markets of other commodities. The crushing process not only yields the oil but also destroys the anti-trypsin factors in the meal; the oil-processing step is therefore essential to the production of the animal-feed grade of meal. However, the oil content of the bean greatly influences the price received by the grower, since they are penalised if the oil content falls below specific norms. The oil content of the bean therefore becomes a critical factor in defining the value of the crop and cannot be permitted to fall as the result of the inclusion of an added trait. As all the beans must be crushed, identity preservation would require dedicated crushing processes to capture a modified oil or soyabean meal.

There is one caveat when the challenges to infrastructure do not apply and that is when the feed quality trait is to be fed directly on-farm, such as many pig producers in northern USA who grow their own grain and dairy producers who produce their own silage. The barriers in terms of infrastructure may also cease to apply in situations where an integrated end user can contract sufficient acres near a local feed mill, assuming that the product can be stored on the farm or at the mill.

One of the most important factors in limiting the numbers of growers who adopt either speciality or bioengineered grains will be the changing value of the crop itself. A premium of US $12 per t for speciality grain when the

Table 2. Costs (US $ per t) to move quality traits through the system

	Maize		Soyabeans	
	Low cost	High cost	Low cost	High cost
Grower premium	4.0	16.0	9.0	37.0
Identity preservation (IP)	4.0	10.0	4.0	66.0
Cost of adoption for end user	–	2.0	–	1.0
IP at processor	–	–	2.0	29.0
Total	8.0	28.0	15.0	133.0

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commodity grain is valued at US $120 per t represents a 10 % increase in value. However, if the commodity crop is valued lower at US $70 per t the same premium represents a 17 % increase in return, which is obviously more attractive. It is predicted that from a low level in 1998–9 the price of grain will steadily rise over the next 7–10 years. The premiums for nutritional traits are generally low, and as the cost of grain increases they represent a diminishing return to the farmer.

High-oil maize: a model for value capture of output traits

HOC is a development in crop production that was adopted by growers and feed compounders as a result of the benefits that can be realised in feed production. Although HOC was a trait achieved by traditional selection and not developed by genetic engineering, the capture of the additional economic value in the crop is an excellent example of the levels of value essential for adoption of the technology and the constraints that may be encountered.

In the first instance the problem of yield lag, which is an immediate constraint and disincentive for the grower, was overcome by using the Top Cross technique. In HOC a double benefit was claimed, the oil concentration rises from 40 to 70 g/kg and there is an additional 10 g protein/kg (from 88·6 to 97·5 g/kg) with additional methionine and lysine. Although there was a reduction in the starch content of the grain, the overall metabolizable energy content increased by 736 kJ (176 kcal)/kg (equivalent to +4·5 %) for poultry. The higher energy and protein content increased the energy and nutrient density of the grain, permitting an increase in overall nutrient density or, alternatively, the use of cheaper feed ingredients as a higher proportion of the ration. The improved protein quality with higher levels of lysine and methionine resulted in a reduction in supplementation with synthetic amino acids.

The primary determinants of the value of HOC as a feed ingredient are the price and nutritional value of normal maize (two-yellow dent maize), and the price of the alternative energy sources, of which the most important is fat. When HOC is used in a typical broiler ration, compared with standard maize, there are two key influences on the value of HOC. First, there is an increase in the value of the HOC in the ration compared with standard maize (US $27.5 per t compared with US $12 per t), but this increase declines as the price of the grain increases. When the price of grain increases, the added value of the HOC declines. This situation at first appears illogical; however, as the price of the grain increases, it is the influence of the least-cost formulation procedure that selects alternative energy sources, and hence the value of the new trait is reduced. The situation is the reverse when the cost of alternative feed ingredients increases. The cost of supplementary fat that would be the alternative energy source has a major influence on the value of HOC. Elevated prices for fat increase the value of the extra energy in HOC. Regional differences in the price of fat influence the potential markets for HOC. It is only in Europe and Asia, where the price of supplementary fat is higher than in the USA, that the value of the additional oil in the maize exceeds the minimum value of US $10 per t (the value, indicated earlier, needed to recompense all the participants in the chain).

The importance of these examples is to demonstrate that several factors influence the value of the added trait. It must be taken into account that feed formulations are derived by least-cost formulation, and that both the cost of the basic grain and cost of potential alternative feed ingredients will crucially influence the value of the trait.

Finally, the value of HOC is also influenced by the effect that the oil content has on feed manufacturing costs. With HOC there is in addition a potential 12 % increase in grinding efficiency, plus other factors such as dust reduction, mixing efficiency and pellet quality. All these factors need to be taken into consideration to determine the final value of the added trait.

Development of protein and amino acid traits in soyabeans

Research into genetically modifying soyabeans has targeted four broad areas: (a) improvement of protein concentration and/or essential amino acid composition; (b) reduction and elimination of anti-nutritional factors; (c) improvement in the profile and composition of soyabean oil; (d) development of disease resistance, herbicide resistance and insect-tolerant lines. The high biological value and relatively high (approximately 440–480 g/kg) protein content of soyabean meal makes it eminently suitable as a protein supplement in rations for pigs, poultry and ruminants. Furthermore, in least-cost formulations soyabean meal has a high value due to its ability to supply lysine. Increasing the methionine content of soyabean meal would improve the amino acid balance of the meal.

Three alternative approaches have been considered for increasing the methionine content of soyabeans using genetic engineering: (a) increase in the free methionine content; (b) insertion of a foreign protein with a high methionine content; (c) replacement of non-essential amino acids in an endogenous protein with the amino acid (methionine). The type of modification may influence the availability of the amino acid.

Increase in the free methionine content of the seed

In many seeds storage proteins are formed from free amino acids. By increasing the free methionine content, i.e. the amino acid is not incorporated into a storage protein, the total methionine content of the seed can be increased. Results suggest that there is the potential to double the total methionine content of the seed by raising the level of free methionine, although the level is limited by the toxicity of the amino acid to the plant. The exact site of the free methionine has not been identified, but it would be important that it did not interfere with the oil extraction process.

Insertion of a foreign protein with a high methionine content

It is possible to express foreign proteins in the storage proteins of seeds. The amino acid composition of the foreign protein can be chosen to include a high level of a specific amino acid, thus increasing the level of that amino acid. The chosen amino acid must represent a high proportion of the foreign protein in order to substantially increase the specific amino acid composition of the seed. Furthermore, it is difficult to find suitable proteins that are completely innocuous. Alternatively, a large quantity of the foreign protein must be inserted into the plant. In this instance it is difficult to maintain the protein–energy balance in the plant. Large quantities of the foreign protein may be inserted at the expense of either the starch or oil content of the plant, since the plant has a limited capacity to manufacture C skeletons. Finally, the availability of the methionine in the foreign protein may be unknown and the level of availability can only be assessed by *in vivo* evaluation. It cannot be assumed that the digestibility of a foreign protein is equal to that of the parent proteins in the plant.

Replacement of non-essential amino acids in an endogenous protein with the amino acid (methionine)

A third approach is that the amino acid of choice (methionine) is used to replace non-essential amino acids in a specific endogenous protein of the plant. To date twenty to forty amino acid residues of the phaseolin protein found in kidney beans (*Phaseolus vulgaris*) have been replaced by methionine. The phaseolin protein was then returned to the parent plant. Such a development has the dual advantage of increasing a specific desirable amino acid and reducing the content of those amino acids not needed. It was claimed that the methionine content of soyabean meal could be increased by 80 % using this technique.

High-protein soyabean meal has the potential to reduce the proportion of meal used in diets for both pigs and poultry. This situation compares with that when individual amino acids are the target. High-lysine soyabean meal, with a 1·3 % increase in the lysine content, would result in a lower proportion of meal in the diet, a higher proportion of feed grains and no supplemental synthetic lysine. The meal would be of greatest benefit to pig producers, but there would be little advantage in the poultry industry. Alternatively, for high-methionine soyabean meal with a 0·32 % increase in methionine content, the primary interest would be from poultry producers, who would be able to reduce reliance on supplemental synthetic methionine.

Chung & Pettigrew (1998) evaluated imputed prices (level of specific nutrient × shadow price) of new soyabeans in a number of formulations to determine the price premiums that could be expected for a range of soyabean meals with different OPT. The estimated imputed prices are considered as the maximum amount of premium prices that livestock producers can pay for each alternative soyabean meal. If livestock producers can gain extra benefit, the estimated prices are the premium prices in the market. However, in reality the premium prices would be determined somewhere between the price of conventional soyabean meal and the imputed price of the new meals, depending on the efficiency of price transmission in the market system. As premium prices approach the imputed price, cost benefits for the livestock producers are expected to decrease. Thus, feed cost savings, estimated by comparing formulas with and without new high-quality soyabean meals and assuming the same ingredient prices, are the maximum estimates of premiums and/or costs savings for the livestock producers. Table 3 is adapted from the data presented by Chung & Pettigrew (1998); their analysis is based on industrial prices for supplementary amino acids and mean commodity prices based on the period from January 1990 to December 1992. The objective of presenting this data is to compare the magnitude of the different premium estimates (rather than considering the actual values, which alter considerably) based on the price of raw materials.

Based on the weighted average values, the highest level of benefit is to be found for the high-protein soyabean meal product in feed for either turkeys or broilers, with approximately equivalent levels of benefit. Although there were positive benefits for layers and pigs, these benefits were less than half those for broilers and turkeys. Such a range in the value that can be captured from the modified crop severely limits its market potential. It would appear, therefore, that

Table 3. Imputed prices* for a range of different soyabean meals (from data of Chung & Pettigrew, 1998)

			Cost savings (US $ per t)		
Animal	Stage	Base model feed cost (US $ per t)	HPSM	HLSM	HMSM
Turkeys	0–4 weeks	148.16	7.97	2.89	4.08
	8–12 weeks	132.32	5.50	5.63	2.83
	16–20 weeks	115.21	3.44	0.07	0.74
	Weighted average	124.99	4.72	2.11	1.89
Broilers	0–3 weeks	148.11	6.44	0.48	3.30
	6–8 weeks	122.21	4.11	0.48	1.75
	Weighted average	129.77	4.84	0.48	2.28
Layers	0–6 weeks	115.63	1.63	0	0.66
	14–20 weeks	99.97	0.46	0.48	0.20
	Laying	105.84	0.99	1.03	1.23
	Weighted average	105.77	0.97	0.89	1.04
Swine	10–20 kg	127.95	5.28	0	NT
	50–80 kg	109.62	1.65	2.42	NT
	Weighted average	111.19	2.05	2.19	NT

HPSM, high-protein soyabean meal; HLSM, high-lysine soyabean meal; HMSM, high-methionine soyabean meal; NT, not tested.
*Level of specific nutrient × shadow price, i.e. the maximum amount of premium prices that livestock producers can pay for each alternative soyabean meal.

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these crops would need to be produced for particular species-specific niche markets. In each instance the highest level of benefit is found in the diet requiring the highest concentration of protein and highest amino acid specification, i.e. in the early growth phase. However, as this stage corresponds to the lowest volume of feed produced, compared with the later growth and finisher phases, the overall value is strongly weighted to that value which can be achieved in the late growing animal. In broilers and turkeys there is an approximate doubling of the added value when the high-protein and high-methionine traits are combined compared with when there is high-methionine only. High lysine content has minimal additional value in broilers and layers and achieves greatest value in pigs, as would be expected.

Based on this analysis, the results indicate that the highest additional value that could be achieved for the high-protein soyabean meal diet was 11 % above the conventional soyabean price. Thus, any premium paid by livestock producers would not be likely to be >11 % on the price of commodity grain. The key question is whether an 11 % increase in the value of soyabean meal is sufficient to exceed US $28, the amount suggested as the minimum required for all the players in the production chain to gain sufficient benefit to invest in the identity preservation of the meal. As has already been emphasized, the answer to this question lies in the number of players in the chain and whether the number can be substantially reduced. Faced with such a challenge there would undoubtedly be an adjustment in the price of synthetic amino acids, reducing the shadow price, with a consequent decline in the imputed price. Chung & Pettigrew (1998) concluded that various price scenarios based on changes in the price of soyabean meal had little effect on predicted savings, and orders in cost benefits remained unchanged. However, changes in the availability of alternative protein sources such as meat-and-bone meal resulted in relatively large effects. This situation is exactly the same as that described for HOC, where the price of alternative energy sources such as fat had a major influence on the additional value of the oil in the grain. Since these alternative sources of energy and protein are by-products of the rendering industry, it must expected that the price of such materials could, and would, be adjusted downwards in the face of a challenge from alternative sources arising in plants.

These calculations presume that the nutritional availability of the added nutrient is not different from that of the original endogenous nutrients in the parent plant. This assumption may be a dangerous one to make, based on the known variability in digestibility of amino acids in a wide range of protein sources. These examples of modification of the amino acid content demonstrate that the market application of specific traits can be highly specific, and that raw materials that presently have universal application can rapidly be restricted to specialised markets.

Improvement of phosphorus availability in grain

There is considerable interest in improving the availability of P in grains as a means of reducing P pollution. Half to two-thirds of the P in plant materials is present as phytic acid, in a form of *myo*-inositol phosphate. Phytic acid binds strongly to P and many other essential dietary minerals, including Ca, Zn, Mg, Fe and Cu, reducing their availability in the digestive tract. Major success has been achieved in reducing the problem by the addition of phytase enzyme to the feed of pigs and poultry.

Two alternatives have been suggested to replace the use of exogenous phytase enzyme. First, the phytic acid content of the seed can be reduced and second, plants can produce phytase-enriched seeds. Stilborn & Crum (1997) reported that a low-phytic acid mutant maize showed an altered relationship between total P and phytic acid. The P released as a result of the reduction in phytic acid content is present as inorganic P. The result is that total P remains the same, but there is an approximately 35 % reduction in phytate and a 65 % increase in available P. Stilborn & Crum (1997) calculated that the estimated additional value for high-available-P maize was for broiler grower, turkey grower and peak-lay layers and was US $1.4, 1.85 and 3.4 per t respectively. This calculation was based only on the replacement of inorganic P in the diet, without additional value for the reduced excretion and management benefits. For maize at US $87 per t the additional value corresponds to 1·6–3·8 % of the maize in diets for broilers and layers respectively. Comparison of these increases in value with those obtained with HOC demonstrates the complexity of the problem, in that it is only when high-available-P maize is used in diets for layers at peak lay that the added value begins to compete with the value of HOC. Obviously, the value for high-available-P maize cannot compete with HOC unless the two traits can be stacked. In a second review of the economic benefits Spencer *et al.* (2000) quoted the benefit in terms of the dietary value for low-phytate maize of US $2.75 per t and an environmental value based on market research that was approximately three times higher (US $8.0 per t). It is obvious that the value of the trait is driven by the environmental consequences. However, producers who are not restricted by the environmental implications will be unwilling to pay the additional price for the crop, and thus some type of two-tier pricing would be required, thus ceasing to be viable.

The alternative to reducing the phytic acid content of the grain is to synthesise phytase in the seed. The European scenario with diets based on wheat shows a similar minimal increase in economic value. Presently, phytase is marketed at a cost of US $1.10 per t feed treated. The price of phytase is limited by the cost of the dicalcium phosphate that the phytase replaces and which is added to feed at a cost of US $1.18 per t feed treated. Currently, without legislation to penalise P excretion, no premium can be added for the benefit of reduced P pollution. Based on a maximum and minimum price for feed wheat over the past 2 years of approximately US $165 and 112 per t respectively and inclusion of 600 g wheat/kg diet, the value of supplying all the additional phytase via endogenous enzyme in the grain is small and only represents an additional value on the price of the grain of 1·6 and 2·4 % respectively. This value is obviously negligible and would not cover the costs of identity preservation of the grain. Such grains would only be of interest as the new commodity grain, and thus the value of the premium for the trait would soon be lost.

Furthermore, quality assurance of either low-phytate grain or, in particular, high-phytase grain would be a major problem. There are presently no routine assays for phytate and phytase, and rapid nutritional evaluation of the crop in the field is required to set a market price.

An economic study was made using least-cost formulation to compare six different types of maize. The effects of the added traits on feed costs for pigs and poultry were determined for each of the modified traits (Baumel *et al.* 1999). For the analysis it was assumed that the cost per t was the same for each of the maize varieties containing the added-value traits. The additional cost of producing the speciality maizes (yield lag, seed cost, handling) was estimated at US $14 per t and was subtracted from the added value of each maize variety to provide a net added value per t for the modified maize (Table 4). A negative value indicates that the additional cost of production exceeded the additional value produced by the trait. The highest overall feed cost savings of US $11.75 per t feed was for formulations utilizing maize with increased protein content, followed by modifications in maize starch digestibility, which reduced the cost of feed by US $7.68 per t. The increased maize germ size lowered feed cost by US $7.06 per t feed. The methionine-enhanced maize saved US $1.57 per t in poultry rations and the lysine-enhanced maize US $2.10 per t for pig diets. The maize with the increased available P yielded the minimum saving of only US $0.12 per t. The poultry diets were the only diets to have positive net values for the six maize modifications. The high-protein and enlarged-germ maize had relatively large positive net values in broiler and tom turkey rations. The diets containing the maize with increased starch digestibility gave an added value of US $2.0 per t for broiler rations only.

It is important to note how the values of the traits differed in terms of the dietary use made of the crop. Where a range of values is obtained for a single trait, it is the lowest value that will allow maximum usage of the crop. There is no precedent to indicate that it is impossible to achieve differential costings for a single raw material. Furthermore, the traits would need to be identity preserved, and some traits would actually impart an apparent negative value when they are not appropriate for a particular species. Such segmentation of the market for a raw material such as maize would require major alterations in the infrastructure of the cereal raw-material markets.

Table 4. Net added value (US $ per t) of each of six genetic modifications of maize used in pig and poultry rations (adapted from Baumel *et al.* 1999)

	Pigs		Poultry		
Modification	Piglet 4–6 kg	Finisher	Broiler	Tom turkey	Layer
High protein (87–167 g/kg DM)	–2.2	–7.7	8.8	4.0	–3.2
Enlarged germ (110–270 g/kg kernel)	–13.8	–9.8	5.0	3.6	0.5
High starch digestibility (+8%)			1.9	–0.63	–1.5
High methionine (×2)			–10.9	–12.2	–11.54
High lysine (×2)	–13.8	–11.7			
High available P (×2)	–13.1	–13.1			

Stacking and multiple trait insertion

The analysis of agronomic IPT given earlier (p. 302) identified the major benefits they bring for the grower. Thus, until a combination of IPT plus OPT can be stacked into plants, there will always be the competition between the choice of the grower for immediate benefit brought about by IPT and the downstream benefits in nutritional value from OPT that must be shared amongst the participants of the feed production chain. For growers, therefore, it is likely that IPT will always be the traits of first choice.

Although techniques of gene insertion are now taken as a matter of course, the simultaneous transfer of several genes is less common, since technically it is more difficult. However, recent developments suggest that simultaneous insertion of agronomic plus OPT may soon be possible. Using ballistic bombardment with plasmids each containing a transgene Chen *et al.* (1998) succeeded in inserting thirteen transgenes into a rice plant.

These results offer considerable promise for the eventual introduction of combinations of traits. Nutritionally-important OPT that could not compete alone, in terms of value when the benefits from agronomic characteristics are an alternative, will become a more attractive choice when there is the option of stacking both OPT and IPT compared with making a choice between one or the other. The opportunity to stack OPT and combine high oil content with high essential amino acid content, and thus substantially increase nutrient density, will increase the value of grain in least-cost formulations, and thus be less sensitive to the changing cost of alternative raw materials. Gene stacking and high nutrient density will be the key to safeguarding the position of GM grain.

Conclusions

Least-cost ration formulation is the corner stone on which feed formulation is based, and this system attributes simple economic values to specific quantities of available nutrients. Nutrients compete with one another on a cost basis. Many of the nutrients that are under consideration for transgenic insertion into plants are presently supplied as commodities with defined prices and nutritional values. The presence of such readily-available and defined commodities places severe limitations on the additional value that can be gained in plants from OPT. Furthermore, for certain traits the value is highly sensitive to the price of the crop and to competing raw materials.

Any yield lag associated with speciality crops will be a major negative factor in relation to the adoption of the crops. There are technological limits to the development of high-level OPT, and their economic evaluation is complex and influenced by many variables. Few OPT are universally applicable and rapid, simple, precise and low-cost methods of analysis are presently not available to quantify the trait on the farm. There are additional hidden costs relative to the handling of the crop that result in a required value over and above that based on the shadow price of the raw material. Contract production, which is not easily accepted by all growers, will be important for the production of crops with quality traits, until the new crop becomes the norm and the new commodity.

On face value OPT offer highly attractive new opportunities for nutritionists. However, the capture of the value is technologically and logistically challenging. Insufficient value within a trait to share within the members of the feed production chain may well limit the adoption of the technology. However, all these problems apart, the present environment is such that consumers, particularly in Europe, have signalled that they are unwilling to accept this new technology. It is important to heed the recommendations made in a recent publication supported by a number of international academies of science, who recommended that transgenic crop research should focus on plants that: (1) improve production stability; (2) give nutritional benefits to the consumer; (3) reduce environmental impact of intensive and extensive agriculture; (4) increase the availability of pharmaceuticals and vaccines (The Royal Society, 2000). There are many OPT developments that will offer, in part, solutions to some of these challenges. If successful they have the potential to lead to a more sustainable agricultural livestock production system than the present and also to remunerate those industries that have accepted the risk to develop the products.

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