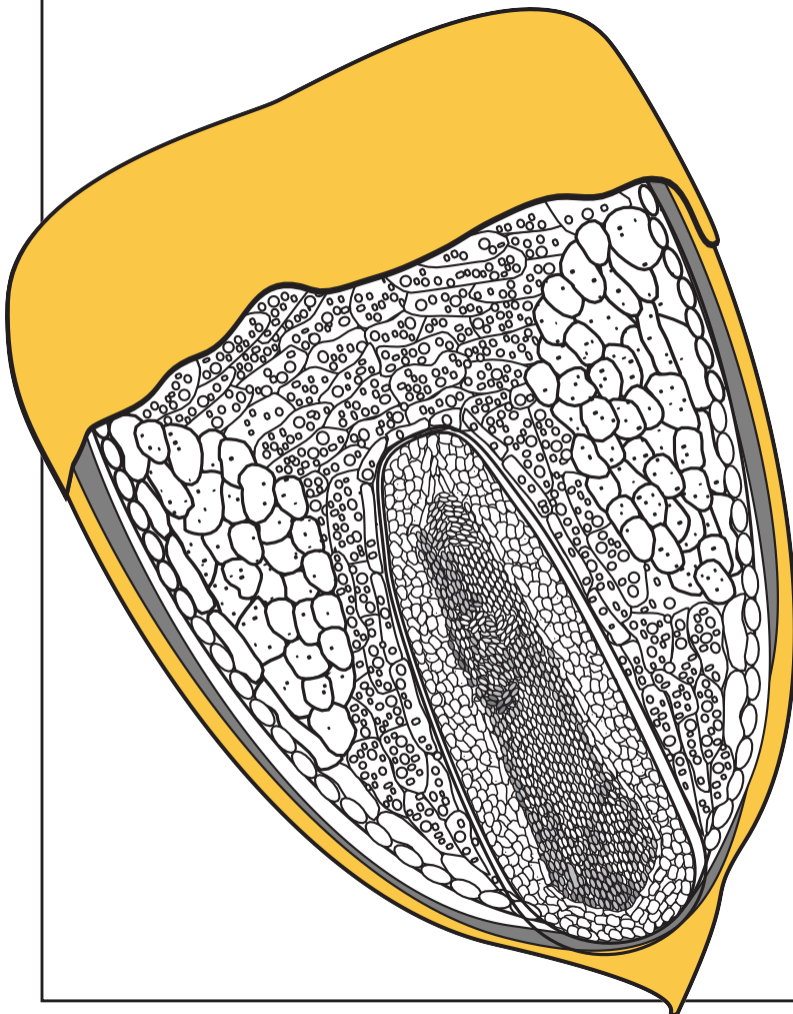


Identifying Valuable Corn Quality Traits for Livestock Feed

A project of the
Iowa Grain Quality Initiative
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Lawrence A. Johnson

Center for
Crops Utilization Research

Connie L. Hardy

Center for
Crops Utilization Research

C. Phillip Baumel

Economics

Tun-Hsiang Yu

Economics

Jerry L. Sell

Animal Science

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**By:
Lawrence A. Johnson
Center for Crops Utilization Research
Food Science and Human Nutrition**

**Connie L. Hardy
Center for Crops Utilization Research**

**C. Phillip Baumel
Economics**

**Tun-Hsiang Yu
Graduate Student, Economics**

**Jerry L. Sell
Animal Science**

**Funded by the
Iowa Corn Promotion Board
306 West Towers
1200 35th St.
West Des Moines, IA 50266**

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**Center for Crops Utilization Research
Iowa Agriculture & Home Economics Experiment Station
Iowa State University, Ames, IA**

Acknowledgments

This report is intended to provoke discussion and debate that will lead to a vision among researchers in public institutions, seed companies, and the feed industry for modifying corn quality traits to enhance its nutrient value in livestock feed applications. This report also attempts to provide direction to farmer organizations and the corn industry about potential targets for investing research funds. One should recognize that some of the modifications considered required speculation about nutrient composition and the limits of enhancing a particular trait. The following individuals provided guidance and insight in this research project.

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Charles R. Hurburgh, Jr., Iowa State University, Ames, IA

Dan Loy, Iowa State University, Ames, IA

Allen Trenkle, Iowa State University, Ames, IA

Bart Waters, Dow AgroSciences, Indianapolis, IN

Dean Zimmerman, Iowa State University, Ames, IA

Executive Summary

Biotechnology, genetic engineering, and traditional plant breeding are rapidly making possible many corn composition modifications that affect livestock feeding. The primary benefits of modified corn for feed are reduced feed costs per unit of weight gain or milk and egg production; reduced animal waste, particularly nitrogen and phosphorus; reduced veterinary costs and improved disease resistance; improved processing characteristics (e.g., reduced dust, ease of grinding or steam flaking, etc.) to make the feed; and improved meat quality (e.g., amounts of lean and fat, fatty acid composition, and other factors having human health implications).

This report covers modifications that affect feed costs and can be evaluated by least-cost feed formulation. In this work, we first considered how new traits would affect grain composition; often making one specific change caused changes in other grain constituents. Corn compositions that reflect enhancements in individual traits were developed and evaluated using the Brill Feed Formulation System for ration balanc-

ing at least cost. Feed savings were then spread over the amount of modified corn used in the diets to arrive at an “added value per bushel.” Allocation of additional value among producers, handlers, seed producers, feed producers, and feeders will be determined by the market.

This study includes determinations of the value of modified corn value in the diets for swine, poultry (layers, broilers, and turkeys) and beef cattle. We also examined different age segments because the needs of very young animals (starters) are different from those of older, mature animals (finishers). Although livestock feeders consider many different age segments, we chose to consider only two—starters and finishers. Diets for intermediate growth stages produce intermediate results.

Twenty-four genetic modifications to corn having potential to reduce feed costs were identified and evaluated. The seven modifications having the greatest annual gross value are listed below:

Modification	Gross Value (billion \$/yr)	Quantity Affected (billion bu/yr)	Added Gross Value (cents/bu)	Added Gross Value Per Unit of Trait (cents/bu)
Increase protein by 8 percentage points	3.45	4.8	72.2	9.0 per percentage point of protein
Enlarge germ for oil (triple oil content)	2.51	5.6	44.8	5.8 per percentage point of oil
Increase germ size to 27% of dry matter	2.06	7.2	28.7	2.0 per percentage point of increased size
Enlarge germ for protein (increase protein content by 7 percentage points)	2.04	8.2	24.6	3.6 per percentage point of protein
Increase starch digestibility by 10 percentage points	1.44	6.7	21.5	2.1 per percentage point of digestibility
Double glutelin protein content	1.18	4.3	27.3	1.8 per percentage point of increased glutelin content in protein
Increase protein digestibility by 10 percentage points	0.88	7.9	11.1	1.1 per percentage point of digestibility

To derive maximum benefits of many modifications, species- and age-specific grains will likely be developed. Many of the modifications envisioned will cause pressure on alternative feed ingredients, especially soybean meal. This may reduce the net financial benefits for some modifications because most midwestern farmers produce both crops.

Introduction

There is tremendous excitement about profit and economic development opportunities that are expected from genetic modification of grain. This excitement is manifested in huge industry consolidation through buyouts, joint ventures, and mergers of seed and agribusiness companies. State and federal government agencies and private organizations have developed programs to encourage and facilitate the production, handling, processing, and marketing of value-enhanced grains, either on a bulk basis or identity-preserved basis. Large investments are being allocated to research and development of new commodities and specialty grains. A large share of research and development funds is being invested in modifying corn because of volume and diversity of uses.

More than 70% of the U.S. corn crop is used in animal feeds either in the United States or at its ultimate export destination; therefore, genetic modifications of corn for animal feed have major profit and development potential. At the same time, the livestock feed industry balances rations to supply nutrients at the least cost. Nutrient sources change, depending on price and availability, so corn that delivers a higher level of nutrients (e.g., protein, energy) will likely substitute for other ingredients in the ration, such as soybean meal and feed fats. Because the demand for feed ingredients is limited by the total demand for meat, milk, and egg products, feed ingredient enhancements may serve only to substitute for other feed ingredients without increasing demand as a whole. However, individual feeders can realize feed cost savings by using corn that delivers higher levels of important nutrients if that type of corn is readily available at the right price. Modified corn also may prove to be a preferred source of certain nutrients for a particular species and growth stage.

The primary benefits of modified corn for feed are as follows:

- Reduced feed costs per unit of weight gain or production of milk or eggs;
- Reduced animal waste, particularly nitrogen and phosphorus;
- Reduced veterinary costs and improved disease resistance;
- Improved processing characteristics (e.g., reduced dust, ease of grinding or steam flaking, etc.) to make the feed; and
- Improved quality (e.g., amount of lean and fat, fatty acid composition, and other factors affecting human health).

This report is an assessment by Iowa State University researchers of possible genetic modifications in corn that could deliver higher levels of nutrients. It focuses on identifying and describing genetic modifications of corn protein, oil, starch, and minerals that might have commercial feed value and on general assessments of the economics of pursuing such modifications. Its purposes are as follows:

- To identify and describe possible modifications of corn that might have commercial feed value,
- To estimate the potential economic benefits that could be derived from each of the identified modifications of corn in feed applications,
- To estimate the amount of modified corn that would be consumed, and
- To rank specific modifications based on potential benefits in feed applications.

Biotechnology, genetic engineering, and traditional breeding are rapidly increasing the likelihood of producing desirable corn modifications. Today, reduced feed cost is the primary market incentive for using modified corn in rations.

Although other benefits also may be realized, we only used feed cost savings to evaluate the modifications described in this report. This study does not consider environmental benefits (e.g., reduced phosphate in manure) of a particular trait because there are not yet market incentives. A subsequent study addresses the effect of price responses in other major feed ingredients to consumption of value-enhanced corn (1).

We recognize that livestock diets are changing. Lower levels of protein are being fed to reduce nitrogen in manure. As this practice becomes widely adopted, protein quality will become more important; therefore, we regard the results of all modifications that affect protein quality to be conservative. Some modifications considered desirable for feed may adversely impact the value of corn for other purposes (e.g., wet milling, dry milling, corn masa, etc.). Specialty corns are likely to be developed for those industries as well, and major benefits are possible (see companion report entitled Identifying Valuable Corn Quality Traits for Starch Production, EDC-194).

Methodology

New traits considered in this report were evaluated in swine, poultry (layer hens, broiler chickens, and turkeys), and finisher beef cattle diets by assigning the same price to modified corn and generic corn. The modified corn was evaluated on the basis of nutrient content. The added value of each modified corn was calculated based on feed cost savings. Some trait enhancements included in this study have been commercialized either individually or in stacked-trait combinations. Scientists from seed genetics companies and university breeding programs contributed composition data that reflect what is currently possible in corn with enhanced nutrients. Other trait enhancements do not yet exist, but were evaluated as if they could be available over a range of levels.

We considered 24 modifications at varying levels in corn and calculated the effects of each modified corn on the cost per ton of balanced rations for each livestock species. For swine and poultry, starter and finisher stages were evaluated. For beef cattle, only the finishing stage of growth was evaluated. Corn compositional changes were intended to enhance digestibility, or to increase nutrient levels that commonly must come into the ration through other ingredients (i.e., soybean meal, dicalcium phosphate, amino acids, feed fat). Typical corn and modified corn compositions were based on long-term averages for the western Corn Belt and industry data for commercial modified corn varieties. Corn compositions were developed to include a range of values for each trait. Most corn compositions were theoretically based on mass balances, and a few were based on actual data provided by seed companies and university breeding programs. Metabolizable energy (ME) and total digestible nutrients (TDN) were calculated using DuPont Estimate v. 2.01,¹ except in the case of starch digestibility. In this case, estimates could be made only by increasing the starch level in the corn and by calculating the effect on metabolizable energy (2).

Feed cost savings were calculated using the Brill Version 7 Feed Formulation System² for ration balancing. Feed ingredient prices published in early May 1997 were used. Nutrient requirements were based on National Research Council and ISU Extension recommendations for age and species (3,4). Feed savings contributed by each trait enhancement were allocated to the bushels of modified corn included in the rations. In this way, feed savings were converted to “gross added value per bushel” for the individual corn modifications in the diets.

Gross values do not reflect any additional costs of producing or handling the modified corn (i.e., seed cost and planting rate differences, reduced yield, additional cost of segregated storage), as would be included in calculations of *net value*. They also do not reflect any market impact of price responses in other major feed ingredients.

Selected levels of increase in a modification were used to calculate the gross value of each trait modification for U.S. corn in the global corn market. Estimates of modified corn consumption were based on domestic corn consumption data from the National Corn Growers’ Association shown in Table 1, and on least-cost, balanced rations calculated using the Brill program.

TABLE 1. Estimated Quantities of Commodity Corn Used in Selected Livestock Rations—United States 1997	
Species	Corn Consumption (million bu/yr)
Swine	1,369
Replacement chickens	76
Broilers	953
Layers	402
Turkeys	294
Beef cattle on feed	1,266
Beef cattle (other)	258
Total	4,618

Source: National Corn Growers Association, St. Louis, MO.

¹ Available through Optimum Quality Grains, West Des Moines, IA.

² Available through the Brill Corporation, Norcross, GA.

Results of Economic Analysis

Least-cost ration balancing models evaluate alternative feed ingredients in diets of swine, poultry, and beef cattle. Using specific assumptions about nutrient requirements, ingredient composition, and price, we used the Brill model to provide consistent balanced rations for each species and age group. In most cases, Brill could accommodate the composition changes in corn from each modification. In a few cases, cost or rations seemed inconsistent within a species or age level, perhaps because the range of variability in corn composition was beyond the model's limits.

Table 2 lists the 24 individual trait modifications and the estimated additional value per unit increase for each trait. Table 3 lists the modifications in order of annual gross value of the enhanced trait at a selected level of increase. Comments are included in the text about relative values of each modified corn in swine, poultry, and beef cattle diets. Some modifications were more valuable in starter diets than in adult or finisher diets. Layer hens are classified by daily feed intake rather than by age and were evaluated at 80-gram or 120-gram levels. Generally, modifications that proved more valuable in starter poultry diets were also more valuable in 80-gram layer hen diets. Following Tables 2 and 3, individual modifications are discussed in more detail.

Protein Modifications

The modifications described below include increases in crude protein content, protein digestibility, selected protein fractions, and individual amino acids. Protein increases are particularly valuable in diets of monogastric (nonruminant) livestock. In swine and poultry diets, certain amino acids are considered “limiting,” so they must be available at specific mini-

um levels for the animal to use dietary protein efficiently. When these amino acids are not sufficiently available, supplemental amino acids may be added to the rations, usually at higher cost. Thus, protein modifications are generally less valuable in finisher beef cattle diets because cattle can build lean tissue mass from less expensive feed inputs.

Increase Protein Content

Protein is usually the most valuable nutrient in livestock diets. Growth and development depend heavily on proteins and their building blocks, amino acids. Typical livestock diets use soybean meal and corn as major protein sources. Increases in corn protein directly affect consumption of corn, soybean meal, and synthetic amino acids, depending on the relative prices of these ingredients.

If crude protein in corn could be doubled (increased by 8 percentage points), feeders of swine and poultry would be able to replace other protein sources (i.e. soybean meal) with modified corn. At this level of corn protein increase, feed savings of \$13.83–18.39/ton in swine diets and \$10.34–34.41/ton in poultry diets are possible. Annually, 4.8 billion bushels of this modified corn could be used in swine and poultry diets worldwide. At an average added value of 72.2 cents/bu, this modified corn could add up to \$3.45 billion in gross value annually to the value of U.S. corn used in world feed markets.

Increase Protein Digestibility

Crude protein in feed ingredients is not totally digestible for any species, but digestibility coefficients have been estimated for important nutrients in the major feed ingredients. Corn protein is approximately 84% digestible for poultry, 82% digestible for swine, and 73% digestible for beef cattle.³

³ Personal communication with ISU Animal Science faculty.

TABLE 2. Benefits and Values of Corn Modifications to Improve Feed

Modification	Benefits	Content of Normal Corn	Estimated Gross Added Value (cents/bu/additional unit of trait)	Gross Added Value of 2x Increase in Trait (cents/bu)
Increase protein content	Replaces soybean meal and some amino acids in the diet	8.7% db	9.0¢/bu per percentage point	78.3¢/bu
Increase protein digestibility	More efficient use of protein	80% ^a	1.1¢/bu ^a per percentage point	11.1¢/bu
Increase lysine content	More of an essential amino acid with added protein	0.3% db	3.8¢/bu per 0.1 percentage point	11.5¢/bu
Increase lysine only	More of an essential amino acid	0.3% db	6.5¢/bu per percentage point	19.5¢/bu
Increase methionine content	More of an essential amino acid with added protein	0.2% db	1.8¢/bu per 0.1 percentage point	3.6¢/bu
Increase methionine only	More of an essential amino acid	0.2% db	3.7¢/bu per 0.1 percentage point	7.4¢/bu
Increase total sulfur-containing amino acids (TSAA) only	More methionine and cystine	0.4% db	2.1¢/bu per 0.1 percentage point	8.4¢/bu
Increase total sulfur-containing amino acids (TSAA)	More methionine cystine, and protein	0.4% db	1.5¢/bu per 0.1 percentage point	6.3¢/bu
Increase tryptophan ^b	More of an essential amino acid with added protein	0.07% db	1.8¢/bu per 0.1 percentage point	2.2¢/bu
Increase tryptophan only ^b	More of an essential amino acid	0.07% db	8.2¢/bu per 0.1 percentage point	9.9¢/bu
Increase threonine ^b	More of an essential amino acid with added protein	0.35% db	0.25¢/bu per 0.1 percentage point	0.9¢/bu
Increase threonine only ^b	More of an essential amino acid	0.35% db	0.25¢/bu per 0.1 percentage point	0.9¢/bu
Increase albumin protein content	More germ protein, lysine, methionine, cystine	7% of protein db	1.1¢/bu per percentage point	7.9¢/bu
Increase glutelin content	More protein, lysine, methionine, cystine, threonine	25% of protein db	1.1¢/bu per percentage point	27.3¢/bu
Increase C-zein and D-zein protein content	More protein and sulfur-containing amino acids	6% of protein db	1.0¢/bu per percentage point	6.0¢/bu

Modification	Benefits	Content of Normal Corn	Estimated Gross Added Value (cents/bu/additional unit of trait)	Gross Added Value of 2x Increase in Trait (cents/bu)
Increase C-zein protein content	More protein, lysine, methionine, cystine	3.3% of protein db	0.9¢/bu per percentage point	2.7¢/bu
Enlarge germ for oil	More energy, protein, and essential amino acids	4.1% oil db	5.8¢/bu per percentage point	23.8¢/bu
Enlarge germ for protein	More energy, protein, and essential amino acids	8.7% protein db	3.6¢/bu per percentage point	30.6¢/bu
Enlarge germ size	More energy, protein, and essential amino acids	11% of kernel weight db	0.2¢/bu for each percentage point	19.9¢/bu
Increase oil content	More energy	4.1% oil db	3.5¢/bu per percentage point	14.0¢/bu
Increase starch content	More energy, but decreased protein and amino acids	71% starch db	0.02¢/bu per percentage point	0.1¢/bu
Increase starch digestibility	More energy without decreasing other nutrients	90% ^c	2.1¢/bu per percentage point	21.5¢/bu
Increase availability of phosphorus	More useable phosphorus	20% of total phosphorus is available	2.9¢/bu per 10 percentage points of availability	5.8¢/bu
Increase phosphorus (total and available)	More useable phosphorus	0.06% of kernel weight is available phosphorus	1.9¢/bu per 0.06 percentage point of kernel weight	3.8¢/bu

^a Protein digestibility was assumed to be 82% for swine, 84% for poultry, and 73% for beef cattle.

^b Swine diets only.

^c Average digestibility was assumed to be 99% for swine, 90% for poultry, and 89% for beef cattle.

TABLE 3. Gross Values of Selected Levels of Corn Modifications in Feed Rations (ranked in order of annual gross value)

Modification	Annual Gross Values (billion \$/yr)	Average Gross Added Value (cents/bu)^a	Quantity of Corn Affected by Modification (billion bu/yr)
Add 8% points of protein	3.45	72.2	4.8
Add 8 points of oil by enlarging germ for oil	2.51	44.8	5.6
Increase size of germ to 27% of dry matter	2.06	28.7	7.2
Add 7% points of protein by enlarging germ for protein	2.04	24.6	8.2
Add 10% points of starch digestibility	1.44	21.5	6.7
Double glutelin protein content	1.18	27.3	4.3
Add 10% points of protein digestibility	0.88	11.1	7.9
Double oil content	0.74	14.0	5.3
Double lysine content and increase protein content	0.48	11.5	4.8
Triple C-zein and D-zein protein contents	0.38	9.8	3.8
Double lysine content only	0.36	19.5	1.8
Double albumin protein	0.33	7.9	4.2
Triple phosphorus availability	0.26	11.7	2.2
Double TSAA content and increase protein content	0.25	6.3	4.0
Double methionine content and increase protein content	0.14	3.6	4.1
Double C-zein protein	0.12	2.9	4.1
Triple total/available phosphorus contents	0.09	3.8	2.3
Double TSAA content	0.08	9.0	0.9
Double methionine content	0.07	7.4	0.9
Double tryptophan content and increase protein content ^b	0.04	2.2	1.7
Double tryptophan content ^b	0.03	9.9	0.3
Double threonine only ^b	0.01	0.9	0.1
Double threonine content and increase protein content ^b	<0.01	0.9	0.1
Add 5% points of starch content	<0.01	0.1	0.4

^a Distributes gross value (\$) over estimated bushels used.

^b Swine diets only.

A conservative increase of 10 percentage points for swine (82–92%), poultry (84–94%), and beef cattle (73–83%) was used to calculate added value in this example. At this level of increased digestibility, this modified corn could produce feed savings in all diets except those for layer hens at the 120-gram feed intake level. Feed savings are greatest in poultry, ranging from \$3.55/ton for 80-gram layer hens to \$5.61/ton for finisher broilers. A 10 percentage point increase in protein digestibility could add nearly \$880 million in annual gross value and nearly 8 billion bushels of U.S. modified corn could be consumed in feed markets worldwide, resulting in an average 11.1 cents/bu added value.

Increase Lysine Content

Lysine is the first limiting amino acid in corn-soybean meal diets for swine. In poultry diets, lysine might be limiting if protein sources other than soybean meal are used. Beef cattle rely on the rumen to supply amino acids, so minimum levels of lysine are not set for cattle diets (5). Thus, the value of this modification is based on feed cost savings in swine and poultry diets only.

This modified corn includes an accompanying small increase in protein with each level of increased lysine; thus, the added value of this modification reflects the protein increase as well as the lysine increase.

Synthetic lysine supplements are often added to corn-soybean meal swine rations, where lysine is the first limiting amino acid. If lysine content were doubled in corn, feed savings would be greatest in swine diets (\$4.65–6.89/ton), but would be \$1.00/ton or less in poultry diets. Additional lysine provides no advantage in beef cattle diets. This modification could add up to \$480 million in annual gross value to U.S. corn in world feed markets and could affect 4.8 billion bushels each year. Mean added value in swine and poultry diets would be approximately 11.5 cents/bu.

Increase Lysine Content Without Changing Protein Content

This modification differs slightly from the previously described lysine enhancement in that

lysine is increased without an accompanying protein increase. When lysine is doubled, this modification is valuable in swine diets and, to a much lesser extent, in starter turkey diets. No other livestock diet is benefited by this modification.

Feed savings in swine diets are in the same range as for the similarly modified corn described in the previous lysine example (\$4.65–6.02/ton). In starter turkey diets, lysine enhancement in corn could save 50 cents/ton. The annual gross value of this modification could add up to \$360 million in world markets for U.S. corn, but would command only 1.8 billion bushels each year. Spreading the additional value over fewer bushels of corn gives this modified corn a higher added value, 19.5 cents/bu, than the modified corn in the previous lysine modification; but, potential market size would be only 43% as large as the market for corn with increased lysine and protein.

Increase Methionine Content

Methionine is the first limiting amino acid in corn-soybean meal diets for poultry, and is the fourth limiting amino acid for swine. Synthetic methionine is often added to swine starter diets and poultry rations (6). Methionine also can be converted to cystine; thus, when no cystine is available, methionine can meet the requirement for total sulfur amino acid (TSAA) (3). This modification assumes an accompanying increase in protein along with a methionine increase. When methionine content is doubled (0.21% db to 0.42% db), protein is increased by 0.2 percentage points. At this level, feed savings are greatest in layer hen diets at the 80-gram intake level (\$3.49/ton), but savings are also significant in broiler starter diets (\$2.99/ton), and in turkey starter diets (\$2.76/ton). Methionine is also important to growth in baby pigs. This modification could produce feed savings of \$1.75/ton in pig starter diets; however, savings in diets for higher growth stages in swine are minimal (\$0.04/ton) because larger animals are able to consume enough protein to meet their methionine requirement.

At the 100% increase level in corn methionine, value additions could reach \$1.62/bu in swine starter diets, and \$1.75/bu in poultry diets. This

modification could add up to \$140 million of annual gross value to corn used in swine and poultry diets worldwide. More than 4.1 billion bushels of modified corn could be used each year at a per bushel added value of 3.6 cents.

Increase Methionine Content Without Changing Protein Content

When methionine content is increased without an accompanying protein increase, feed savings and added value are nearly the same as when both methionine and protein contents increase. Feed savings are greatest in swine starter diets (\$1.77/ton) and poultry starter diets (\$1.55/ton), and in diets for 80-gram layer hens (\$1.76/ton). In swine starter diets, the greatest savings are found when methionine is increased up to 50%, but less modified corn is used when methionine alone increases beyond 50%. Finisher broiler diets require much less modified corn as methionine content increases, so feed savings are less significant at higher growth stages.

In this analysis, the high-methionine corn was replaced with less expensive protein sources in poultry finisher diets and in diets for 120-gram layer hens. If methionine content doubled (increased by 100%), the annual gross value of this modified corn in swine and poultry feed markets could reach \$68 million. However, demand for this corn would be approximately 900 million bushels each year, less than 25% of the demand for corn with increases in both methionine and protein.

When only methionine content is increased without a related increase in protein content, least-cost programs will include only enough modified corn in the rations to fill the methionine requirement and then use an alternative protein source. Therefore, fewer bushels of modified corn will be used each year (900 million in this example), but each bushel of modified corn will be worth 7.4 cents/bu compared with 3.6 cents/bu for high-methionine corn with increased protein content.

Increase TSAA Content

TSAs comprise the sum of methionine and cystine. These amino acids must be present in feed

to allow proper growth and development through adequate protein formation. Deficiencies of TSAA can decrease rate of gain, so supplementation with methionine is sometimes necessary to meet minimum dietary requirements (methionine can be converted to cystine). When TSAA content is doubled there is a corresponding increase in crude protein content of 0.5 percentage points.

Baby pigs benefit from an increase in TSAA up to a point. In starter pig diets, increasing the content of TSAA by 50–100% achieves maximum feed savings (\$1.76/ton), whereas increases above 100% result in less modified corn being used in the diet because the need for TSAA is met.

Poultry diets can benefit proportionally with increases in TSAA, even above the 100% increase level. Feed savings range from \$1.52/ton to \$4.62/ton in broiler and turkey diets, respectively. Savings of \$4.35/ton are possible in 80-gram layer hen diets, whereas savings in 120-gram layer hens are low by comparison (\$0.91/ton).

From a worldwide feed perspective, a 100% increased TSAA in corn could add \$250 million annually in gross value to U.S. corn, potentially affecting 4.0 billion each year. An average of 6.3 cents/bu of added value could be realized. As with other amino acid modifications, this corn is not valuable in finisher beef cattle diets.

Increase TSAA Content Without Changing Protein Content

TSAs are important to growth and development of lean tissue. As in the previous example where the levels of TSAA in corn were increased, the greatest feed savings were in starter diets of swine and poultry, and in diets for 80-gram layer hens. Without additional crude protein, increased levels of methionine and cystine are less useful in diets beyond the starter level. At the adult level, rations will usually include less modified corn and more protein from soybean meal under the price conditions used for this analysis (May 1997). Older animals can consume enough feed to meet the TSAA requirement from alternate protein sources.

If the TSAA content is doubled in corn and the protein level does not increase, feed savings in starter swine diets could reach \$1.75/ton. In poultry diets, feed savings are highest in starter diets, ranging from \$3.41 to \$4.25/ton. In finisher broiler and 120-gram layer hen diets, small feed savings (\$0.32–0.69/ton) could be realized and less modified corn would be used in the rations. On a worldwide basis, only 0.9 billion bushels of this modified corn could be used each year, resulting in up to \$84 million in annual gross value for U.S. corn in these markets. Because this additional value is spread over fewer bushels of corn than in the previous example of increased TSAA content, the average added value per bushel is greater, 9.0 cents/bu compared with 6.3/bu for corn with increased TSAA and protein contents.

Increase Tryptophan Content

Tryptophan is usually considered the second limiting amino acid in swine diets. Minimum levels of tryptophan have been established in swine rations for proper use of lysine and arginine (3). Although tryptophan also is considered important in poultry diets, minimum levels have been established only for broilers up to 3 weeks in age. Therefore, tryptophan levels were evaluated only in swine diets for this study.

In May 1997, the price of crystalline tryptophan supplement was \$3.27/lb. Under these price conditions, doubling tryptophan content with a modest increase in corn protein could produce feed savings of 77 cents/ton in finisher swine diets and produce an average added value of 2.2 cents/bu. In swine diets alone, increasing tryptophan by 25% produced nearly the same feed savings as a 100% increase in tryptophan while maintaining a high level of modified corn in the diet. Gross additional value of this modification could reach \$35 million and affect 1.7 bushels of U.S. corn in swine diets worldwide.

Increase Tryptophan Content Without Changing Protein Level

If tryptophan level doubles without an accompanying protein increase, feed savings of 70 cents/ton could be realized in swine diets with an average added value of 9.9 cents/bu. Additional gross

value of U.S. corn with this modification could reach \$32 million in finisher swine diet applications. The Brill model included significantly less modified corn in the ration at the 100% increase level of tryptophan (17.9% modified corn versus 91.2% modified corn), which resulted in less demand (322 million bushels) and higher per bushel added value (9.9 cents/bu) for this modified corn compared with corn in which tryptophan and protein were both increased.

Increase Threonine Content

Threonine is usually the third limiting amino acid in corn-soybean meal diets for swine. It has been shown to improve performance when added to a corn-based diet (3) and may be added as a crystalline supplement to swine starter diets (6). In May 1997, crystalline threonine cost \$200/lb, whereas lysine was priced at \$7.40/lb and methionine at \$1.38/lb. Under these price conditions, if the threonine content could be doubled with an accompanying protein increase, feed cost savings could reach \$1.04/ton in starter swine diets, but finisher swine diets did not show feed savings with this modified corn. Feed savings reached a maximum and remained constant after threonine was increased by 75%. This modification could affect 148 million bushels of U.S. corn in swine diets worldwide with an annual added gross value of up to \$1.3 million. Additional value per bushel for increased threonine with the related protein increase would be approximately 1.0 cent/bu.

Increase Threonine Content Without Changing Protein Content

An increase in threonine alone produces nearly the same results as increases in threonine and protein as previously described. Feed savings in starter swine diets could reach \$1.07/ton if the threonine content were increased. As before, maximum feed savings occurred at the 75% increase level and remain constant as threonine is increased above that level. Additional gross value, bushels of corn affected, and added value per bushel are the same as when threonine and protein are both increased; \$1.3 million, 148 million bushels, and 1.0 cent/bu, respectively.

Increase Albumin Protein Content

Albumin proteins are biologically active proteins (mostly enzymes) and contain higher proportions of essential amino acids than corn storage proteins (zeins). Corn typically contains 7% of its total protein as albumin proteins (6). The quality of the amino acid composition of this protein fraction is preferred in nonruminant livestock nutrition; thus, increasing this class of proteins improves the overall amino acid balance of corn protein.

If albumin protein content is doubled, starter and finisher diets in swine and poultry could realize feed savings. Generally, savings in finisher diets exceed those in starter diets, probably due to the greater proportion of modified corn that would be used in finisher diets. For swine, savings of \$1.43/ton in starter diets and \$2.49/ton in finisher diets could be realized. Savings in poultry diets range from \$0.94 to 2.54/ton, usually exceeding \$1.50/ton except in diets for 120-gram layer hens. This modification could add up to \$330 million in gross value to U.S. corn, yielding an average added value of 7.9 cents/bu and commanding 4.2 billion bushels of modified corn.

Increase Glutelin Content

The glutelin protein fraction in corn is a rich source of amino acids such as lysine, methionine, and cystine that may be limiting amino acids in swine and poultry diets. Corn typically contains 25% of its total protein as glutelin proteins, which reside primarily in the germ (6). Increasing glutelin protein improves overall amino acid balance in corn protein for feed applications.

If glutelin content could be doubled with a corresponding increase in protein of 2.2 percentage points, glutelin would then comprise 40% of the protein and provide greater amounts of limiting amino acids (e.g., lysine, methionine) in swine and poultry diets. Feed savings of \$2.84–8.87/ton in poultry diets and \$4.78–4.86 in swine diets are possible at this level of increase, with a mean added value of 27.3 cents/bu for this modified corn. In world feed markets for U.S. corn, the additional annual gross value of doubling the glutelin content of corn could

reach \$1.18 billion and would affect approximately 4.3 billion bushels of U.S. corn each year.

Increase C-Zein Protein Content

Increasing C-zein protein in corn is another strategy for increasing methionine and cystine. Corn typically contains 3.3% of its zein protein as C-zein, which is unusually high in TSAA (7). This modification includes very modest increases in crude protein (0.15 percentage points of crude protein when C-zein is doubled), so the modification's value is based mainly on increased TSAA content.

When C-zein is doubled, feed savings are highest in broiler diets and 80-gram layer hen diets at \$1.37/ton. Finisher turkey diets can reach savings of \$1.22/ton. Starter swine diets have comparatively small savings of 22 cents/ton. This modification could be worth up to \$120 million in gross added value for 4.1 billion bushels of U.S. corn in world feed markets annually. The average added value is 2.9 cents/bu, though added value in poultry feed applications is 3.5–7.0 cents/bu.

Increase C-Zein and D-Zein Protein Content

Zein proteins are found in corn endosperm and are distinctly different in amino acid composition than proteins found in corn germ. They are classified according to amino acid composition and named with letters (A, B, C, etc.). Zein protein represents 52% of total kernel protein in corn (7). C-zein and D-zein comprise 5.9% of zein protein and are particularly rich sources of methionine, the first limiting amino acid in poultry diets, and of sulfur-containing amino acids (7). Identifying and increasing corn protein fractions that provide larger amounts of limiting amino acids may provide feed cost savings by avoiding the use of higher cost supplements. However, finisher beef cattle diets would not gain any savings from this corn modification.

Increased contents of C-zein and D-zein proteins with an accompanying increase in total protein content generally produce greater feed savings in starter poultry and swine diets than in finisher diets. If C-zein and D-zein protein

contents could be tripled, feed savings in swine starter diets could reach \$2.43/ton. The range of feed savings in poultry starter diets is estimated at \$5.94–9.09/ton, and savings in 80-gram layer hen diets could reach \$9.57/ton. Mean added value is approximately 9.8 cents/bu, resulting in additional annual gross value of up to \$380 million in the world feed markets using 3.8 billion bushels of modified corn each year.

Germ Size Modifications

Enlarge Germ for Oil

This modification describes corn composition that is typical of commercial high-oil corn. Increased germ size provides primarily more oil content, but protein content also modestly increases. Germ proteins provide high-quality protein in the diet, so any increase in germ protein is likely to be beneficial in terms of amino acid balance.

Several levels of oil increase (up to 16% oil db) were examined using actual data provided by seed companies. If the oil content was increased three times that of typical corn (12% db), protein content increases 5.5 percentage points (14.1% db), and starch content decreases 13 percentage points (58.2% db). Additional energy and high quality proteins are provided in this modified corn. Diets for swine, poultry, and beef cattle show feed savings, except diets for 120-gram layer hens. Today, commercial high-oil corn typically contains 6 or 7% (db) oil; but, experimental hybrids contain more than 20% oil.

When oil content is tripled with accompanying changes in protein and starch, feed savings are highest in broiler starter diets (\$50.22/ton). Savings in swine diets ranged from \$8.37/ton to \$10.44/ton, and savings in finisher beef cattle diets are \$6.24/ton. Finisher turkey and broiler diets show savings of \$23.31/ton and \$28.14/ton, respectively. Swine and poultry diets show maximum feed savings at an oil content of 12%, whereas beef cattle diets show increasing feed savings proportional to the increase in oil. At 12% oil content, this modified corn could add up to \$2.51 billion of annual gross value to U.S. corn used in livestock diets worldwide with an average

added value of 44.8 cents/bu. Approximately 5.6 billion bushels of corn per year would be affected.

This modification provides both protein and energy, and thus produces substantial savings in feed rations. This modification affects more corn than those that increase only protein because the energy portion is valuable in both ruminant and monogastric diets. Compared with modified corn in which only protein increases, high-oil corn shows lower aggregate and per bushel added values because its value is affected by the prices of both soybean meal (a relatively high-cost protein source) and feed fat (a relatively low-cost energy source).

High-oil corn provides other nonquantifiable benefits. Increased tocopherols provide antioxidant activity to improve flavor stability in feed rations and improve the quality of frying fats in which poultry are prepared. In addition, diets that include high-oil corn result in slightly more saturated poultry fat, which is preferred in deep-fat frying applications.

Enlarge Germ for Protein

Another strategy for increasing energy and protein level is to enlarge the germ size and to select for protein content increasing faster than oil content. Corn of this type is commercially available as “high-protein corn.” For this analysis, we used actual composition data of high-protein corn varieties provided by seed companies. If the protein content increases by 7 percentage points (15.7% db), oil content increases by 2 percentage points (6.1% db).

Feed savings in swine and poultry diets increase steadily as protein and oil contents increase, except in diets for 120-gram layer hens. At the 15.7% protein level in this high-protein corn, swine diet feed savings range from \$4.63/ton (starter) to \$7.16/ton (finisher). Poultry starter diets and 80-gram layer hen diets show feed savings of \$7.10/ton to \$25.37/ton, whereas finisher diet feed savings average \$21.25/ton for broilers and turkeys. Beef cattle diets show savings of less than 40 cents/ton, probably due more to the increased energy level than to the protein increase.

Of all the corn modifications considered, this one would be likely to increase U.S. corn consumption the most, affecting an estimated 8.3 billion bushels per year with an annual gross added value up to \$2.04 billion. The average added value (24.6 cents/bu) is below that of other corns with enhanced oil and protein because the estimated annual gross value of \$2.04 billion is spread over 8.3 billion bushels. In swine, poultry, and beef cattle diets, the amount of modified corn in the diet increases as protein content increases. Thus, high-protein corn is likely to compete heavily with soybean meal as a protein ingredient in feed rations.

Enlarge Germ Size

This is a theoretical evaluation of enlarging the germ and retaining the relative proportions of oil and protein in normal corn. Increased amounts of germ protein provide more high-quality protein in the diet because germ proteins contain higher levels of essential amino acids needed by swine and poultry. No seed companies have merely enlarged the germ and maintained the proportions of oil and protein in normal corn. Rather, they have selected for enlarged germs with either increased oil content, increased protein content, or increased albumin content. Germ comprises about 11.1% of the kernel weight in typical corn (8). This analysis describes feed savings and added value when the germ size is increased to 27% of the kernel weight (a 144% increase over the typical germ size), with protein content at 10.3% db, oil content at 8.7% db, and starch content at 61.1% db.

Feed savings increase at each level of germ size up to 27%, then level off or decrease for finisher swine and poultry. Beef cattle and 80-gram layer hens showed constant increases in feed savings at germ sizes larger than 27%. For finisher broilers and turkeys, feed savings of \$15.15/ton are possible if germ size increases to 27%. Feed savings for starter broilers and 80-gram layer hens average \$11.75/ton and, in starter turkey diets, \$4.42/ton. In swine finisher diets, feed savings could reach \$10.30/ton, but were less in starter diets at \$2.12/ton. Beef cattle finisher diets could realize feed savings of \$2.46/ton, but no feed savings are possible in diets for 120-gram layer hens.

This modified corn could have an annual gross added value of up to \$2.06 billion to U.S. corn in world feed markets and could command 7.2 billion bushels of corn each year. In feed markets for swine, poultry, and beef cattle, use of this corn could add 1 billion bushels to current world demand for corn, but would likely decrease demand for soybean meal. Average added value is estimated at 28.7 cents/bu.

Oil Modifications

Increase Oil Content

High-oil corn usually contains higher levels of germ protein that affect nutrient values in feed rations. In this modification, oil increases at the expense of protein and starch, providing more metabolizable energy in the rations. Significant feed savings are possible in poultry and beef cattle diets; but increased oil, by itself at any level, is not important in swine diets nor in diets for 120-gram layer hens. This analysis covers oil levels up to 16% (12 percentage points above typical corn) and show increasing feed savings in poultry diets up to 6% oil. From 6 to 12% oil levels, feed savings decline gradually, then drop rapidly after 12%. Only beef cattle diets show increasing feed savings at oil levels more than 12%.

If corn oil content doubles (to 8.1% db), finisher diets for turkeys and broiler chickens show the greatest feed savings at \$6.82/ton and \$6.51/ton, respectively. Feed savings for broiler starter diets are \$5.36/ton and less in turkey starter diets, \$1.71/ton. Layer hen (80-gram) diets could benefit by savings of \$5.77/ton, but no savings are possible in diets for 120-gram layers. Finisher beef cattle diets may realize savings of \$3.88/ton.

At this level of oil increase, up to \$740 million in annual gross added value would be achieved in feed applications using U.S. corn worldwide, and 5.3 billion bushels of corn could be affected each year. Estimated average added value is 14 cents/bu, or 3.5 cents for each additional percentage point of oil.

Starch Modifications

Increase Starch Content

This modification would increase starch content (71% db in normal corn) with accompanying decreases in protein and oil contents. Corn with starch contents of 76% db (5 percentage points of additional starch) are only valuable in 120-gram layer hen diets where feed savings could reach 25 cents/ton. In this application, 428 million bushels of U.S. corn could be used worldwide each year, but additional value per bushel would be low at 0.1 cent/bu. Additional gross value is estimated to be less than \$500,000 per year.

Increase Starch Digestibility

This modification examines the potential for altering the structure of starch to facilitate more complete digestion in the small intestine where it is used for weight gain. Increased starch digestibility could be a valuable modification in U.S. corn, especially for broiler chickens and finisher beef cattle, if the benefits of increased digestibility can be demonstrated and feeders convinced of the benefit of increased starch digestibility. Although new information is changing perceptions among scientists, corn starch is considered by the feed industry to be 99–100% digestible for swine and poultry. This may be true over the total tract, but only the digestion that occurs in the small intestine contributes to weight gain. Some poultry nutritionists have recently estimated corn starch digestibility could be as low as 82% (9).

In this analysis, starch digestibility is increased by 10 percentage points, which theoretically makes it nearly 100% digestible. In this case, finisher diets for turkeys and broiler chickens could realize the highest feed savings, \$9.57/ton and \$9.20/ton, respectively. Starter broiler and 80-gram layer hen diets could realize savings of \$7.81/ton and \$8.42/ton, respectively. Starter turkey diets could realize \$2.37/ton in feed savings, but no savings are predicted for 120-gram layer hens. Savings of \$2.46/ton are possible in beef cattle diets. In all species, feed savings steadily increase as starch digestibility increases.

With 10 percentage points of increased starch digestibility, this modification could have an annual gross value of up to \$1.44 billion to the value of U.S. corn used worldwide in feed applications. Approximately 6.7 billion bushels of corn could be consumed each year with an additional value of 21.5 cents/bu.

Phosphorus Modifications

Convert Unavailable Phosphorus to Available Phosphorus

This modification examines the potential of converting unavailable phosphorus (phytate-bound phosphorus) into available phosphorus, which would likely produce feed savings for all livestock except 120-gram layer hens and beef cattle. Approximately 20% of the total phosphorus in corn are available to meet the needs of livestock; the remainder is present as undigestible phytate and is not biologically available. Lines very low in phytate have already been developed (lines with 65% of the phosphorus in available form have been achieved) (10). Unavailable phosphorus is excreted and contributes to environmental problems. Environmental costs of phosphorus in waste were not factored into our analysis, only feed savings due to reduced need for dicalcium phosphate were considered.

When the amount of available phosphorus in corn is tripled (up to 60% available), feed savings are greatest in diets in 80-gram layer hen diets (87 cents/ton), starter broilers (82 cents/ton), starter turkeys (69 cents/ton), and starter swine (42 cents/ton).

Finisher diets might realize savings, but they would be less than 50% of the savings in starter diets. At this level of phosphorus availability, approximately 2.2 billion bushels of corn could be consumed each year at an average added value of 11.7 cent/bu. This modification could contribute up to \$260 million in annual gross value to U.S. corn in world markets for feed savings alone, not considering the environmental impact of reducing phosphorus.

Increase Total and Available Phosphorus Contents

This modification may provide an alternative route to increasing available phosphorus content by increasing total phosphorus, but would exacerbate phosphorus in waste problems. In this example, a 37% increase in total phosphorus would provide as much available phosphorus as in the previously described modification where phosphorus was 60% available. However, due to limits in the least-cost ration-balancing model, this modification adds only approximately one-third as much value to corn in the ration and adds an annual gross value up to \$90 million. This modification could produce 3.8 cents/bu of added value, while affecting the same amount of corn (2.2 billion bushels). By increasing total phosphorus content, there is a negative environmental impact, which was not considered.

Conclusions

Modifications in corn composition produce feed cost savings on balanced corn–soybean meal based rations for swine, poultry, and beef cattle. Under the market conditions in May 1997, corn and soybean meal were at relatively high prices. Both ingredients are major protein sources and, along with animal and vegetable fat, provide energy in the diet; the remaining diet ingredients provide amino acids, vitamins, minerals, and antibiotics. When nutritional traits are enhanced in corn, the modified corn will likely substitute for another major ingredient, usually soybean meal, synthetic amino acids, or fat, thus affecting consumption of other major feed ingredients.

When considered together, these 24 modifications could affect far more corn than is currently demanded by feed markets, and some modifications are substitutes for other modifications. Therefore, it is likely that corn modifications will be stacked to convey greater nutritional advantages and increase added value.

When feed savings are allocated across the total bushels of modified corn that could be used, the modifications with the greatest additional value per unit of increase are as follows:

- Increased protein content (9.0 cents/bu per 1.0 percentage point of increased protein),
- Increased tryptophan (8.2 cents/bu per 0.1 percentage point of increased tryptophan),
- Increased lysine (6.5 cents/bu per 0.1 percentage point of increased lysine),
- Increased lysine and protein (3.8 cents/bu per 0.1 percentage point of increased lysine),
- Increased methionine (3.7 cents/bu per 0.1 point of increased methionine),
- Increased oil content (3.5 cents/bu per 1.0 percentage point of increased oil), and
- Increased available phosphorus (2.9 cents/bu per 10 percentage points of increased phosphorus availability).

The annual gross added values at a selected level of each trait enhancement also were estimated using average added value and potential modified corn consumption. The modifications having the highest gross added values are as follows:

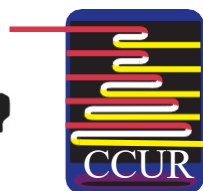
- Additional 8 percentage points of protein (\$3.45 billion),
- Enlarged germ for oil so that oil content is increased 8 percentage points (\$2.51 billion),
- Enlarged germ size to 27% of dm (\$2.06 billion),
- Enlarged germ for protein so that protein content is increased 7 percentage points (\$2.04 billion),
- Additional 10 percentage points of starch digestibility (\$1.44 billion),
- Glutelin protein content is doubled (\$1.18 billion), and
- Additional 10 percentage points of protein digestibility (\$880 million).

To derive maximum benefits of many modifications, species-specific and age-specific grains will likely be developed. Many of the modifications will cause pressure on alternative feed ingredients, especially soybean meal. This may reduce the net financial benefits to producers for some modifications because most midwestern farmers produce both crops.

Decisions on whether to grow modified corn will depend on net value rather than gross value. Net value reflects the additional costs of production, storage, and handling as well as price response of competing feed ingredients. This study is the first step in determining the real value of each of these modifications.

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Center for Crops Utilization Research

Iowa State University, Ames, IA 50011

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