Economic Viability of High Digestibility Sorghum as Feed for Market Broilers

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ABSTRACT

Recently, improved lines of the high-lysine mutant of grain sorghum [*Sorghum bicolor* (L.) Moench] have been shown by Hamaker, Axtell, and coworkers at Purdue University to have substantially greater digestibility of protein than normal cultivars. These lines exhibit substantially greater digestibility of protein than normal cultivars. Here, we seek to estimate the value of high digestibility sorghum (HDS) relative to regular sorghum for market broilers. To do this, nutritional characteristics of HDS derived from laboratory tests were incorporated into a least-cost feed mix linear programming model. The model was used to optimize rations for starting and grown-for-market broilers (*Gallus gallus domesticus*) in poultry production for three age categories: 0 to 3 wk, 3 to 6 wk, and 6 to 8 wk. The base model established a premium value on HDS of $1.54, $1.24, and $0.96/t for use as feed for chicks in the three corresponding age ranges. Sensitivity analysis was performed with respect to objective function coefficients and HDS amino acid digestibility. Over a range of historical and regional prices, the inclusion of HDS was relatively stable, and average premiums for HDS derived were close to or above base model values. From amino acid digestibility parametric analysis, it was found that the premium on HDS increases essentially linearly with improvements in digestibility over the 0 to 10% range.

Recently, new lines of grain sorghum [*Sorghum bicolor* (L.) Moench] in a high-lysine background have been identified by Hamaker, Axtell, and coworkers at Purdue University. In lab tests, these lines exhibit substantially greater digestibility of protein than normal cultivars (Weaver et al., 1998). Based on this finding, the economic potential of high digestibility sorghum (HDS) for use as feed for animals, in processing industries such as brewing, and as a staple food for human consumption in semiarid regions of Africa and India warrants investigation. Here, we seek to estimate the value of HDS relative to regular sorghum for market broilers in three age categories. By examining the value of HDS across three age categories, we also hope to provide insight into appropriate marketing strategies for early adopters of HDS.

BACKGROUND

Sorghum as Feed

Currently, about 48% of world sorghum grain production is fed to livestock. Sorghum is often compared to maize [*Zea mays* var. *indentata* (Sturtev.) Bailey], for which it is a close substitute. It has similar feed characteristics, provides about as much metabolizable energy, has a higher crude protein content, but less digestibility. Overall, total digestible nutrients in sorghum are roughly 95% of those in dry rolled yellow dent maize. This nutritional deficiency relative to maize is primarily believed to be due to lower starch availability because traditional sorghum starch content varies and is bound in a tighter and thicker protein matrix. Regular sorghum, therefore, becomes attractive as feed only when its price declines to less than about 95% of the maize price. Consequently, international sorghum prices move very closely with those of maize and are usually about 5% lower (FAO, 1996).

As usual, this general story masks considerable variation. For example, the nutritional value of sorghum grain is different for ruminants than for nonruminants. In ruminants, micro flora of the rumen can upgrade poor-quality proteins and nonprotein N to the protein quality of the micro flora itself. Therefore, ruminant nutritionists view sorghum and other cereal grains, primarily as sources of carbohydrates (e.g., starch). In nonruminants, sorghum is also viewed mainly as an energy source; however, the quality and quantity of the protein is more important than for ruminants. For example, for broilers fed cereal grain–based diets, proteins from cereal grains can contribute more than one-third of total dietary crude protein. The importance of cereals as a protein source for broilers combined with the relative proximity of important broiler and sorghum producing regions, such as Arkansas and Texas, explain the decision to focus on broilers in this first economic assessment of HDS.

Traditionally, depressed growth and feed conversion have been observed when regular sorghum grain high in tannin has been substituted on an equal basis for maize in practical poultry diets (Hulan and Proudfoot, 1982). Conner et al. (1969) showed that the growth depression and inferior feed conversion might be related to the level of tannin present. This is the main reason why regular sorghum was not fed to poultry in the past. Modern sorghum varieties are low in tannin. For modern varieties, it was first reported in the literature that chicks fed diets containing sorghum exhibited poorer weight gains and, in some cases, inferior feed efficiency compared with chicks fed a maize-based diet (Rostagno et al., 1973). These results were later refuted by Hulan and Proudfoot (1982), who found that starter and finisher broilers fed with different sorghum levels in the diet had no significant effect on their mean live weights. More recently, a chick feeding study by Hancock et al. (1990) showed improvements in rates and efficiencies of gain, relative to maize, when normal sorghum lines were selected with higher in vitro digestibility.

High Digestibility Sorghum

In 1975, Axtell and colleagues (Mohan, 1975) developed a chemically induced mutant P721 Opaque (P721Q) with 60% more lysine than normal sorghum. The enhanced lysine content of that line resulted primarily from an increase in the lysine-rich nonkafirin and a small decrease in the amount of the lysine-poor kafirin proteins. Weaver et al. (1998) reported the discovery of sorghum lines within a population derived from crosses of P721Q and hard endosperm, food-grade sorghums that have substantially higher uncooked and cooked protein digestibilities compared with normal sorghum cultivars. Results from laboratory tests are reported in Table 1.

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Abbreviations: HDS, high digestibility sorghum; LP, linear programming; RHS, right hand side.

Table 1. In vitro digestibilities (pepsin, %) using pepsin assay of two normal sorghum cultivars and three sorghum cultivars from high-lysine population (Weaver et al., 1998).

		1992 Digestibility tests		1994 Digestibility tests	
Cultivar	**Protein content†**	**Uncooked**	**Cooked**	**Uncooked**	**Cooked**
	%				
Normal sorghum cultivars					
P721N	**11.8**	**80.2b‡**	**56.8b**	**70.9b**	**48.5c**
SAFRA	**12.6**	**65.8c**	**57.8b**	**73.5b**	**47.3c**
Avg.	**12.2**	**73.0**	**57.3**	**72.2**	**47.9**
HDS population cultivars					
P851171	**11.8**	**87.0a**	**80.8a**	**88.3a**	**72.5a,b**
P850029	**12.7**	**87.8a**	**78.7a**	**89.4a**	**75.1a**
Avg.	**12.2**	**87.4**	**79.7**	**88.8**	**73.8**
Difference between HDS and normal					
HDS-normal	**0.0**	**14.4**	**22.4**	**16.6**	**25.9**

† By micro-Kjeldahl method.
‡ Values in the same column followed by the same letter are not significantly different ($P < 0.05$).

Higher protein digestibilities of these improved lines were shown to be a result of more rapid digestion of the main sorghum storage protein, α-kafirin. This protein alone comprises approximately 60 to 70% of total grain protein. Highly digestible grain was of a floury kernel type, though recently the high digestibility trait has been found in a modified kernel type with partial vitreous endosperm (Weaver et al., 1998).

In addition to the importance of finding sorghum cultivars with high protein digestibility, Weaver et al. (1998) also provide a potential explanation of why normal sorghum has poor protein digestibility when compared with other cereals. They theorize that sorghum protein in normal cultivars is less digestible because the protein bodies are more resistant to proteolysis than the protein bodies of other similar cereal grains such as maize (Hamaker et al., 1987; Oria et al., 1995a). Various experimental evidence implicates the enzyme-resistant nature of the peripherally located γ-, and possibly β-, kafirins that prevent ready access of proteases to α-kafirin. Additionally, γ- and β-kafirins have been shown to form extensive intermolecular disulfide-bound complexes during seed development and during cooking (Oria et al., 1995a, 1995b). In a companion study on the same highly digestible lines, Oria et al. (2000) found γ-kafirin to be located not at the body protein periphery, but at the base of folds of a highly invaginated protein body structure. Thus, α-kafirin in protein bodies of the highly digestible cultivars is more exposed to digestive enzymes than in normal protein bodies, and, accordingly, is quickly digested (Weaver et al., 1998).

METHOD

Determining least cost feed mixes is a classic application of linear programming (Waugh, 1951; Beneke and Winterboer, 1973). And linear programming (LP) remains the principal tool employed to choose among feedstuffs when formulating balanced rations for livestock feed. To use LP in ration formulation, the question, "What feedstuffs should be fed?" is reduced to purely mathematical terms that obey the principles of nutrition and economics (Pesti and Miller, 1993). Linear programming is used to find the combination of feedstuffs that meet certain specifications (mainly nutrient requirements) at the lowest cost. This is called the *least-cost feed formulation*. When LP is used, economic information, in the form of shadow prices and reduced costs, is also generated beyond the minimal feed cost and the shares of each feedstuff in the ration. Shadow prices indicate the incremental cost of increasing an arbitrary nutrient requirement by one unit while holding all others constant. Reduced costs indicate the incremental cost of forcing one unit of an unused feedstuff into the optimal solution. Alternatively, reduced costs can be viewed as the amount the objective function coefficient (feed stuff price) must decline before that activity enters the ration.

Generally, a least cost feed mix LP problem may be expressed in the following form:

$$Min \sum_{j=1}^{N} C_j F_j$$

$$s.t.$$

$$(1) \sum_{j=1}^{N} a_{ij} F_j \leq UL_i \quad \forall\ i = 1,2,...,M$$

$$(2) \sum_{j=1}^{N} a_{ij} F_j \geq LL_i \quad \forall\ i = 1,2,...,M$$

$$(3) \sum_{j=1}^{N} F_j = 1$$

$$F_j \geq 0 \quad \forall\ j = 1,2,...,N$$

where F_j is the number of units of feed ingredient j in the mix, C_j is the unit cost of ingredient j, a_{ij} is the amount of nutrient i in one unit of ingredient j, and UL_i and LL_i represent, respectively, upper and lower limits on characteristic i of the mix. The objective is to minimize the cost of formulating one unit of the ration subject to three blocks of constraints that ensure acceptable composition of the feed. For example, an equation in Constraint Block 1 could be used to impose a maximum amount on any given feedstuff (to avoid problems with palatability, for example). An equation from Constraint Block 2 could be used to impose minimum energy requirements. The single equation in Constraint Block 3 ensures that the total weight in the ingredients in the feed equals the total required weight.

To assess the expected premium value for HDS, nutritional characteristics of HDS derived from laboratory tests were incorporated into a least-cost feed mix LP model. Sensitivity analysis or parametric linear programming was used to assess stability of the solution with respect to variations in the prices of available ingredients and assumptions regarding protein availability. Results from the sensitivity analysis were used to help define future research strategies and to identify critical parameters of HDS for poultry nutrition.

DATA AND EMPIRICAL MODEL DEVELOPMENT

Sixteen feed sources (labeled activities in LP jargon and represented by X in our general formulation), covering the most common poultry feeds, were made available in the LP model. The ration must be formulated through some combination of these 16 feedstuffs. The model chooses a combination of feedstuffs, weighing no more than 1 kg, that meets nutritional requirements while minimizing cost.

1. Alfalfa (*Medicago sativa* L.) meal dehydrated with 17% of protein.
2. Barley grain (*Hordeum vulgare* L.).
3. Brewer's grain dehydrated.
4. Dent yellow maize (*Zea mays indentata*) gluten meal with 60% protein.
5. Dent yellow maize grain (*Zea mays indentata*).
6. Fish Menhaden (*Brevootia tyrannus*) meal mechanically extracted.
7. Meat meal rendered.
8. Poultry feathers meal hydrolyzed.
9. Sorghum grain [*Sorghum bicolor* (L.) Moench].
10. High digestibility sorghum grain [*Sorghum bicolor* (L.) Moench].
11. Soybean [*Glycine max* (L.) Merr.] seeds, meal solvent extracted [SoyMeal48].
12. Wheat grain (*Triticum aestivum* L.) hard red winter.
13. Cotton (*Gossypium* spp.) seeds, meal prepressed solvent extracted with 41% protein.
14. Calcium phosphate, dibasic form defluorinated phosphoric acid.
15. Animal–vegetal fat blend.
16. Sodium chloride, NaCl.

Regular sorghum grain and HDS were considered to have exactly the same nutrient profile except with respect to protein digestibility. Digestibility rates in HDS were set to 10% above the rates for regular sorghum. This was accomplished by increasing availability to the bird (e.g., increasing the coefficients in the constraint matrix) of arginine, histidine, isoleucine, leucine, lysine, methionine, methionine + cystine, phenylalanine, valine, and threonine by 10%. Crude protein content was left the same between regular sorghum and HDS. The 10% increase in amino acid availability is a conservative estimate. The improvements in digestibility indicated in Table 1 for uncooked and cooked sorghum grains substantially exceed 10% for all cultivars.

Nutrient content for these feed inputs (the a_{ij} in the general formulation), divided into 35 separate nutrients, were obtained from the National Research Council (NRC, 1994). These values are averages reflecting the concentration of nutrients most likely to be present in the selected feedstuffs. (In a few instances, the NRC values were adjusted to reflect improved information; see Dowling, 2000.) For essential amino acids, the NRC (1994) reports estimates of essential amino acid concentrations based on changes in total crude protein content. Specifically, essential amino acid concentrations in each feedstuff are related to total protein content by a series of linear functions estimated statistically using regression analysis by the NRC (1994). However, since uncooked proteins vary markedly in their digestibility, total amino acid concentrations estimated by the NRC (1994) are not fully available to broilers. Therefore, total amino acid contents were multiplied by true digestibility coefficients (also taken from NRC, 1994) to calculate the amount really available to the bird. These corrected relationships between total protein availability and amino acid concentrations were incorporated into the model.

In addition, composition of feedstuffs on an as-fed basis was corrected to 90% dry matter. The dry matter correction was performed to have nutrient content of feedstuffs expressed in the same concentration basis as broiler requirements. The units of the feedstuffs themselves are on a standard (not dry matter) basis. Also, in the NRC data, the problem of gross content vs. amount truly available also exists for P since requirements for this mineral are stated as nonphytate P and feedstuffs contributions are stated as total P. Therefore, when appropriate, total concentration was converted to nonphytate P.

Requirement values for the 35 nutrients in the model (the values of LL_i in the general form above) were also taken from the NRC (1994, page 27). These requirements "are generally minimum levels that satisfy general productive activities and (or) prevent deficiency syndromes." Requirements were collected for three specific age categories: 0 to 3 wk, 3 to 6 wk, and 6 to 8 wk. Nutrition requirements in the model were also adjusted to represent true digestible amino acid requirements consistent with the availability adjustments made for the selected feedstuffs.

In addition to the nutrient requirements, a special restriction was imposed to maintain a ratio of arginine to lysine $\geq$1.14:1. This special restriction was included because of evidence of an antagonism between these amino acids. In the case of arginine–lysine, an excess of lysine can adversely affect metabolism of arginine.

Precise requirements of most minerals in practical diets are not well defined because practical diets are usually adequate or only slightly deficient in these minerals. However, it is known that an excess of dietary Ca interferes with the availability of other minerals, particularly P. A ratio of approximately 2:1, Ca/nonphytate P (wt/wt) is appropriate for most practical diets. A special constraint was included to maintain exactly this 2:1 ratio for any ration formulated. Finally, although substantial research has been conducted for most vitamins, the requirements for practical diets are not well defined, and practical diets are not usually markedly deficient in vitamins.

Feedstuff prices are a final, and very important, input into the model. Since relative prices will be a key determinant of model results, a number of relative price combinations from different sources are employed. Each price data source has advantages and drawbacks. In the base model, average feed prices calculated from published historical series (for years 1975–1997) are employed as coefficients of the objective function (the values of C_j in the general formulation). Average prices, in dollars per tonne, and sources for the price series are shown in Table 2. Average prices have drawbacks, only one of which is the elimination of price variation. To extend the analysis to a series of relative price relation-

Table 2. Activities reduced cost and objective coefficients in \$/t.†

Feed ingredient	Broiler categories			Objective coefficients
	0–3 wk	3–6 wk	6–8 wk	
Alfalfa meal 17%	0.00	0.00	0.00	112.32
Barley grain	0.00	0.00	0.00	95.98
Brewer grain	0.00	−48.98	−61.42	129.85
Maize Gluten60	−14.97	0.00	23.06	260.49
Maize grain	0.00	0.00	0.00	112.95
Menhaden	0.00	0.00	0.00	381.2
Meat meal	0.00	0.00	0.00	213.15
Poultry feathers	188.80	12.67	42.10	228.49
Sorghum grain	1.59	1.24	0.96	107.14
HDS grain	0.00	0.00	0.00	107.14
SoyMeal48	0.00	0.00	0.00	184.32
Wheat grain	24.46	15.10	14.73	139.17
Cotton meal	−102.91	−50.79	−52.79	159.44
Dicalcium phosphate	0.00	0.00	0.00	207.39
Fat	0.00	−21.12	−30.42	347.00
Salt	0.00	0.00	0.00	60.96

† Sources for objective coefficients (prices): *Feed Yearbook* (USDA-ERS, 1999). Barley no. 2 or better feed (Duluth, MN), maize no. 2 yellow (Gulf), sorghum no. 2 yellow (Gulf), and wheat hard red winter (Gulf) are average cash prices at specified markets. Alfalfa meal 17% (Kansas), brewer's grain (Lawrenceburg, IN), maize gluten 60 (Illinois), fish menhaden (East coast), meat meal (central USA), poultry feathermeal (Arkansas), soybean meal 48 (Decatur), cottonseed meal (Memphis), and animal–vegetable fat blends are average wholesale price, bulk at specified markets. *Chemical Marketing Reporter* (Schnell Publ., 1975–1997). Dicalcium phosphate and salt evaporated common, bulk.

ship, the model was solved for each year of price data from 1975 to 1997. This provides an idea of what premiums might have been had HDS existed in the past.

The use of published historical price series is attractive from the vantage points of clarity, verifiability, and reproducibility of results. However, the historical series reflect the influence of government policy and ingredient quality. Changes in government policy or ingredient quality might substantially influence relative prices making the historical analysis misleading for the current/future price environment. A further disadvantage is that the price series generally come from major markets for each product, and these markets are geographically widely dispersed. Spatial price variation may imply that the sorghum–poultry regions in focus in this analysis experience different relative prices than the major market ratios would suggest. Consequently, prices for major ingredients from 1995 to 1997 for eastern Texas, collected and disseminated by Agri-Stats (2000), are also employed in a round of analysis.

In all model runs, HDS is priced at the same level as regular sorghum. In both the published historical series and the data from eastern Texas, the sorghum/maize price ratio is <0.95. As a result, sorghum competes well with maize in the LP model.

Finally, maximum boundaries on use (UL_i in the general formulation) for many feedstuffs were set to avoid toxicity and palatability problems. Further information on data and data sources, as well as a complete exposition of all model equations, can be found in Dowling (2000).

RESULTS AND ANALYSIS

Basic Model Solution

The model was used to optimize rations for starting and grown-for-market broilers in poultry production for the three age categories defined above (0–3 wk, 3–6 wk, and 6–8 wk). Each category has a different set of right hand side (RHS) values corresponding to different nutritional requirements (the LL vector in the general formulation). As a first step, optimal rations were developed using historical average feed prices. The cost of the ration (the objective value) and the percent participation of each feedstuff in the optimal formulation for each category are reported in Table 3.

Table 3. Percent composition and objective values of the optimal least cost formulation for different broiler categories using average prices.

	Broiler categories		
Activity level	0–3 wk	3–6 wk	6–8 wk
Objective value†	160.74	153.43	149.62
		%	
Alfalfa meal 17%	1.79	2.20	2.57
Barley grain	0.91	11.29	18.36
Brewer grain	3.96	5.00	5.00
Maize Gluten 60	5.00	2.37	0.00
Maize grain	3.05	1.66	0.74
Menhaden	2.06	1.65	4.17
Meat meal	4.82	4.47	2.33
Poultry feathers	0.00	0.00	0.00
Sorghum grain	0.00	0.00	0.00
HDS grain	45.32	41.59	42.27
SoyMeal48	20.06	16.10	11.17
Wheat grain	0.00	0.00	0.00
Cotton meal	5.00	5.00	5.00
Dicalcium phosphate	1.77	1.53	1.31
Fat	5.98	7.00	7.00
Salt	0.27	0.15	0.09
Total	100.00	100.00	100.00

† The units of the objective are \$/t of feed. This value corresponds to the cost of the ration.

High digestibility sorghum is the single largest component of the ration for all categories of broilers. The share of HDS ranges from 42 to 45%, depending on age. As mentioned above, the primacy of sorghum in the ration over maize is due primarily to a favorable sorghum/maize price ratio. At the prices employed, regular sorghum would serve as the primary grain if HDS were excluded. This is the situation that prevails in sorghum growing regions. Since area currently planted to regular sorghum represents the most obvious initial market expansion opportunity for HDS, a focus on feed mixes composed primarily of sorghum is appropriate.

In the optimal diet, the share of grain (primarily HDS and barley) increases with the age of the broilers. This is consistent with the evolution of nutrient requirements of chicks. Younger chicks require a diet richer in protein while older chicks require a diet richer in energy. Since grains are primarily an energy source, the share of grains in the ration tends to rise. Similarly, the share of the primary protein source, SoyMeal48, declines rapidly with age.

Reduced costs for the activities and for different broiler categories are reported in Table 2. The reduced costs are the shadow prices on the upper and lower bounds for the variables (*0* and UL_i in the general formulation). A zero reduced cost indicates that the activity (feedstuff) is employed at a level strictly in between the upper and lower bounds. A negative reduced cost indicates the activity is employed at the upper bound while a positive reduced cost indicates the activity is employed at the lower bound (zero in this case). For binding upper bounds, the reduced cost provides information on how much the value of the objective function (total feed cost in this case) would decline if the upper bound on an activity (feedstuff) were increased by one unit. For binding lower bounds, the reduced cost indicates by how much the objective coefficient (feed stuff price) must decline before that activity enters the ration.

In Table 2, the bounds for barley grain and alfalfa meal are not binding for any broiler category, and their reduced costs are zero. Brewer's grain, cotton meal, fat, and maize gluten have some binding upper bounds reflected by negative reduced costs. Maize appears in the optimal solution of all rations at a level below the maximum, and thus also exhibits zero reduced cost. Wheat has to reduce its average market price of \$139/t by \$24/t to be included in the optimal solution for broilers between 0 and 3 wk of age.

Since the nutrient vectors of regular sorghum and HDS are the same except with respect to protein digestibility, the reduced cost on regular sorghum provides insight into the premium value associated specifically with the high digestibility characteristic. The greatest value differential between regular sorghum and HDS is expressed for broilers between 0 and 3 wk old. Here, the price differential is \$1.59/t in favor of HDS. This means that HDS, given the price and nutrient assumptions embedded in the model, has an extra intrinsic value of \$1.59/t, which amounts to 1.5% of the sorghum price. The same line of reasoning applies for the other two categories, where the extra intrinsic value is \$1.24/t for broilers between 3 and 6 wk and \$0.96/t for broilers between 6 and 8 wk old.

A second means for examining the implications/value of HDS is through the impact of HDS on total feed cost. When HDS is excluded from the optimal ration developed above, costs increase by 0.45, 0.32, and 0.27% for the three age categories running from youngest to oldest. The HDS sorghum reduces cost primarily through reductions in the volume of purchase of protein sources such as soybean meal.

The decline in the premium associated with HDS across age categories follows from the evolution of nutrient requirements as the chicks age. Since protein requirements decline in relative terms as chicks age, the premium associated with additional available protein in HDS declines as well.

At this point, some discussion of the incidence of the efficiency gains from HDS may be worthwhile. A number of potential gainers from introduction of HDS can be identified. These include seed suppliers (through premiums on HDS seed), farmers (through premiums on HDS sorghum), makers of mixed feed (through lowered cost of formulating a balanced ration), poultry producers (through lowered cost of rations), and consumers (through lower cost of poultry). Obviously, the same gain cannot be had twice. So, if seed suppliers manage to sell HDS at a premium, there will be reduced gains to be shared throughout the remainder of the value creation chain.

The literature on technical advance usually postulates an S-shaped or logistic adoption curve (the seminal work is Griliches, 1957). Essentially, there are three periods associated with adoption of an innovation: an early period with adoption undertaken by a few innovative individuals, an intermediate period where adoption rapidly becomes widespread, and a final period where a small group of laggards gradually adopts the technology. In agriculture, early adopters usually gain the most from the technology since market reactions, which often shift the incidence of gains away from farmers, have not yet occurred. In the aggregate, the story of technical change in 20th century agriculture has been that the gains from technical advance in agriculture have accrued primarily to consumers in the form of lower food prices (see Paarlberg and Paarlberg, 2000, for an excellent and comprehensive discussion).

Supposing that the benefits of HDS are passed entirely to consumers, we can make a back-of-the-envelope assessment of the benefit. Feed costs represent about 60% of production costs for broilers and production costs represent about 25% of the retail price (USDA-ERS, 2000). Assuming that use of HDS reduces total feed cost (across the age classes) by 0.3%, then the drop in retail prices is very minor—$<$0.1%. Nevertheless, with more than 8 billion head of broilers raised in the USA in 1999, even small cost reductions can add up. The total gains to consumers would depend on the volume of HDS use and the extent of benefit pass-through to consumers.

The benefits of technical change in agriculture in the aggregate has, over the past century, clearly accrued primarily to consumers in the form of lower prices; however, the story with respect to specific advances, such as HDS, is less clear. Specific technical advances have also catalyzed reallocations of benefits within the agricultural sector. One would require a formal model and substantial analysis to fully flesh out all of the distributional impacts of widespread adoption of HDS sorghum (which might differ between the short and the long run). This exercise goes beyond the scope of this paper. Nevertheless, two facts about sorghum indicate HDS adoption might cause reallocation of benefits within the agricultural and/or processing sectors rather than pass through to consumers. First, the total value of U.S. corn and soybean production, the two primary inputs into mixed feed for broilers, exceeded the value of U.S. sorghum production by factors of 17 and 12, respectively in 1999 (USDA-ERS, 2001b). Second, area devoted to sorghum production is circumscribed by agronomic considerations. While improved technology in sorghum might cause area in sorghum to expand somewhat at the margin, the value of sorghum production will, in all likelihood, remain small relative to corn and soybean.

Under these conditions, the marginal (e.g., additional) feed source for poultry will be corn and soybean. The prices of corn and soybean will remain the primary elements determining the feed cost of producing an additional broiler. If the prices of the marginal feed sources (corn and soybean) do not decline as a result of HDS, then consumer prices for broilers are unlikely to decline either. The LP results presented above indicates that one should expect HDS to command a higher price relative to corn and soybean than traditional sorghum for use as feed in market broilers. Given the relative sizes of the corn, soybean, and sorghum markets, one would reasonably expect, even in the long run, the relative price adjustment to occur essentially entirely through an increase in the price of HDS sorghum as opposed to a decline in the price of corn and soybean. If the price of HDS rises relative to corn, the long run beneficiaries will be land-owners (mostly farmers) in sorghum-producing regions. The rise in the land rental rate maintains the competitive market equilibrium condition of zero economic profits in sorghum production.

The maximum premium of $1.59 represents only 1.5% of the price of sorghum. Nevertheless, even small premia could be quite significant for sorghum producers. Using national sorghum budgets developed by the USDA (USDA-ERS, 2001a) for 1999, one can examine the first order impact of changes in price on farm profits. If producers planting HDS received a 1.5% price premium, corresponding to the benefits calculated for farmers marketing sorghum for broilers between 0 and 3 wk old, it would imply an improvement in net operating margin (revenue less operating costs) of 7.5%. Smaller premiums lead to commensurately lower benefits. These net return improvements assume that HDS yields the same and costs no more to grow compared with regular sorghum. The yield assumption is consistent with available field trial evidence (Hamaker, personal communication, 1999). The cost assumption might be violated, especially for early adopters of HDS, if HDS seed is more expensive than seed for regular sorghum. In this case, some of the premium associated with HDS would be absorbed by the seed supplier.

Sensitivity Analysis

Solutions to LP models are notoriously fragile. Large changes in the character of a solution can occur for small changes in underlying data. As a result, investigation of the robustness of LP solutions through sensitivity analysis is important. Standard sensitivity analysis is based on the proposition that all data except for one exogenous input into the model are held fixed. It provides information about the effect on the optimal solution (quantities of ingredients used) and optimal value (cost of the ration) of changing this single piece of data (such as price, nutrient content of an ingredient, or nutrient requirement).

However, traditional sensitivity analysis provides only limited insight for two main reasons. First, the results are only relevant for a specific range of values of the varying exogenous input. One might be interested in effects beyond that range. Second, the requirement that only one variable change is strongly limiting. In reality, some exogenous variables tend to move in tandem, such as maize and sorghum prices. To study the implications of changes across a wide range of values for a specific exogenous variable or changes in more than one exogenous variable, the model is solved repeatedly for sets of exogenous variables and the characteristics of the various solutions compared. This more detailed form of sensitivity analysis was performed with respect to objective function coefficients and HDS amino acid digestibility.

As indicated above, the sensitivity of results to changes in objective function coefficients was first analyzed by iteratively solving the model using annual average prices for each of the 16 feedstuffs prevailing over the period 1975–1997. This permits one to assess the role and value of HDS sorghum across a range of observed relative prices.

Figure 1 shows the shares of HDS sorghum in the optimal rations for each of the three categories. The shares are reasonably stable, especially for chicks 0 to 3 wk old (two data points excepted). Importantly, the shares almost never fall below 25% for any of the age categories. This consistent entry of HDS sorghum into the optimal solution is likely to be attractive to makers of mixed feed. Institutionally, it can be inconvenient for makers of mixed feed to deal with an ingredient that

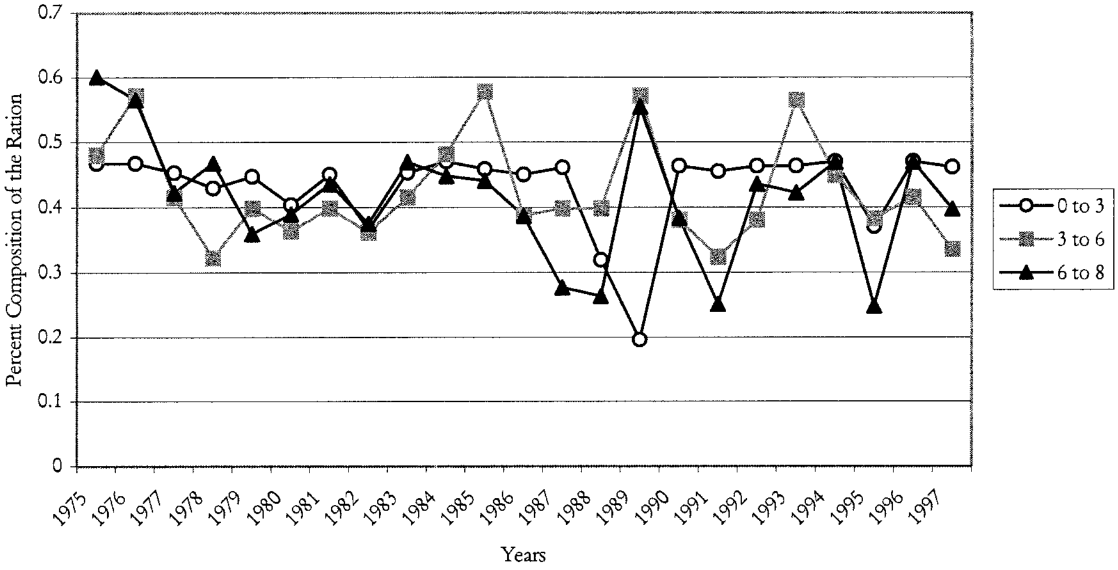

Fig. 1. High digestibility sorghum participation in the optimal solution for historical prices.

Table 4. Average premium over regular sorghum.

	Broiler category		
Parameter	0–3 wk	3–6 wk	6–8 wk
Avg. ($/t)	1.94	1.23	0.84
SD	1.22	0.49	0.58
t-statistic†	7.61	12.11	6.89
Avg. (% of sorghum price)	1.83%	1.19%	0.80%

† The critical value at the 95% confidence interval is 1.72.

occasionally enters the optimal solution and occasionally does not.

To assess the stability of the premium on HDS over regular sorghum obtained using average feed prices, the average reduced cost associated with regular sorghum was calculated from the solutions to the LP model for each year from the historical price series. Regular sorghum average reduced costs for different broiler categories, both in absolute value and as a percentage of the regular sorghum price, are reported in Table 4. These average reduced costs are qualitatively similar to the values obtained using average historical prices, but the tendency to favor younger chicks is more pronounced. For chicks 0 to 3 wk old, the average reduced cost is \$0.35/t higher than the value obtained using average prices while, for chicks 6 to 8 wk old, the average reduced cost is \$0.12/t lower. Standard deviations indicate the premium does vary with relative price shifts for each of the three categories. For example, the premium in each year varied from 0.6 to 5.6% of the sorghum price for that year for chicks 0 to 3 wk old. The hypothesis of a mean reduced cost of zero was rejected under the assumption of a *t* distribution for all age categories.

To examine relative values in sorghum growing regions, prices for primary ingredients for eastern Texas from Agri-Stats for the years 1995–1997 were employed. Agri-Stats provided information on prices for maize grain, meat meal, sorghum grain, soybean meal, dicalcium phosphate, fat, and salt. (These prices are available from the authors upon request.) For the 3 yr of eastern Texas prices, these seven ingredients represented about 75% of the optimal ration for chicks age 0 to 3 wk old. For the ingredients comprising the remaining 25% of the ration sensitivity analysis indicated little change in the premium on HDS with respect to changes in these ingredient prices.

Table 5 illustrates the premiums derived from the model using the 3 yr of eastern Texas data. Due to relatively high commodity prices during the period 1995–1997, the absolute value of the premiums are typically higher than the values derived in the base model using the average of the published price series. (The premiums calculated for the period 1995–1997 using the published historical price series are also above average.) The premium values as a percent of the sorghum price are quite consistent with the results presented in Tables 2 and 4.

Further sensitivity analysis using the average of the 1995–1997 eastern Texas prices indicates the premium (in absolute value terms) is more sensitive to the price of protein sources. For example, if the price of primary protein sources (alfalfa meal, menhaden, meat meal, soybean meal, and cotton meal) is reduced by 10%, the premium on HDS sorghum falls by 17% on average. A reduction of 10% in the prices of primary energy sources (barley grain, maize grain, and regular and HDS sorghum) leads to an 11% decline in the premium.

Next, sensitivity analysis for HDS amino acid digestibility changes for broilers between 0 and 3 wk old was explored. This category was chosen because it appears to have greater potential for use of HDS. This potential is expressed through the stable appearance of HDS in the optimal diet through time and the relatively large reduced cost differential (premium) between regular sorghum and HDS.

High digestibility sorghum amino acid digestibilities were set equal to regular sorghum values (i.e., the 10% improvement was eliminated). At this point, HDS and regular sorghum nutrient vectors are exactly the same. Digestibility of HDS sorghum was then gradually increased to the 10% improvement and then beyond; the premium on HDS sorghum relative to regular sorghum was recorded. The premium on HDS increases in essentially a linear manner. So, using eastern Texas prices, the premiums for a 1% improvement in digestibility are approximately 0.1 the values for a 10% improvement in digestibility listed in Table 5. At greater than 10% digestibility enhancement, the benefits of increased digestibility decline with the decline depending on the price vector employed. By 15% increased digestibility, the marginal value of additional digestibility had dropped to zero for all price vectors.

SUMMARY AND IMPLICATIONS

Summary of Results

Recently, new lines of grain sorghum, which exhibit substantially greater digestibility of protein than normal cultivars, have been identified. Here, we have sought to estimate the value of high digestibility sorghum (HDS) relative to regular sorghum for market broilers. To do this, nutritional characteristics of HDS derived from

Table 5. Premium values on HDS using eastern Texas prices.

	Age categories					
	0–3 wk		3–6 wk		6–9 wk	
Year	Value	Percent of sorghum price	Value	Percent of sorghum price	Value	Percent of sorghum price
	$/t	%	$/t	%	$/t	%
1995	2.45	2.17	1.64	1.45	0.35	0.31
1996	2.73	1.74	1.33	0.85	1.72	1.10
1997	2.83	2.46	1.46	1.27	1.31	1.14
Avg.	2.67	2.13	1.48	1.19	1.13	0.85

laboratory tests were incorporated into a least-cost feed mix linear programming model. The model was used to optimize rations for starting and grown-for-market broilers in poultry production for three age categories: 0 to 3 wk, 3 to 6 wk, and 6 to 8 wk.

In the model base run, average historical prices were used and the model was solved independently for broilers in the three age categories. In addition, the model was solved for historical feedstuff price combinations and recent prices in a specific growing region (eastern Texas) to assess stability and identify critical parameters (parametric analysis). For all the alternatives, HDS was priced at the same level as regular sorghum.

High digestibility sorghum comprised the major feed portion in the basic model for all broiler categories. Furthermore, HDS was never excluded from the ration. Across the three age categories of broilers analyzed, HDS use almost never fell below 25% of the ration and never rose above 60% of the ration when subjected to the annual price vectors prevailing between 1975 and 1997.

Comparing the value of HDS relative to regular sorghum, the base model established a premium value on HDS of $1.59/t or 1.5% of the sorghum price for use as feed for chicks between 0 and 3 wk old. In the historical analysis, premiums ranged from 0.6 to 5.6% of the regular sorghum price. For the eastern Texas price data, premiums were higher in absolute value but similar in terms of percent of the sorghum price to those obtained using average historical prices. If this benefit manifested itself as a price premium on HDS sorghum, net farm returns would have increased by about 7.5% in 1999. Since older chicks require a diet that is less rich in protein, premium values are lower for the older age classes. The base model estimated premiums were $1.24/t for broilers between 3 and 6 wk and $0.96/t for broilers between 6 and 8 wk old (slightly more and slightly less than 1% of the sorghum price for the two classes, respectively). While the historical analysis does indicate that these premiums are sensitive to changes in feed input price vectors, average premium values are all significantly different from zero.

Sensitivity analysis was also performed for HDS amino acid digestibilities. The premium on HDS increased essentially linearly with improvements in digestibility over the 0 to 10% range. The marginal benefits of additional digestibility declined above 10% and reached zero for all price vectors at the 15% level.

Limitations of the Study and Future Research

Practical poultry diets are usually optimized considering fewer nutritional restrictions than employed in this model. However, using fewer restrictions to optimize the model, particularly with respect to amino acid availability, would substantially impair our ability to compare HDS with regular sorghum as poultry feed. The first objective of this research was to generate such information.

Hamaker and coworkers speculate that rapid digestion of protein may translate into higher starch availability. Experiments are currently underway to determine if this is, in fact, the case. This higher energy availability was not considered in the model because of incomplete information about the higher values of metabolizable energy that HDS can achieve. Since sorghum is mainly an energy source, higher starch content would further improve HDS performance relative to regular sorghum as broiler feed.

Finally, other than the sensitivity analyses undertaken, uncertainty was not considered in the model. It is well known that nutritional composition of feedstuffs can be highly variable. Total protein content and amino acid digestibilities are also highly variable parameters (Hulan and Proudfoot, 1982). The unique structure of HDS sorghum might reduce variance in digestibility relative to normal sorghum. Starch availability and variance in nutrient availability are important topics for future research.

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REFERENCES

Agri Stats. 2000. Specially requested data. Agri Stats, Fort Wayne, IN.

Beneke, R.R., and R. Winterboer. 1973. Linear programming applications to agriculture. Iowa State Univ. Press, Ames, IA.

Conner, J.K., I.S. Hurwood, H.W. Burton, and D.E. Fuelling. 1969. Some nutritional aspects of feeding sorghum grain of high tannin content to growing chickens. Aust. J. Exp. Agric. Anim. Husb. 9: 497–501.

Dowling, L.F. 2000. An economic assessment of nutritionally enhanced high digestibility sorghum for market broilers. M.S. thesis. Purdue Univ., West Lafayette, IN.

Food and Agriculture Organization of the United Nations. 1996. The world sorghum and millet economies. Facts, trends and outlook. FAO, Rome.

Griliches, Z. 1957. Hybrid corn: An exploration in the economics of technical change. Econometrica 25:501–522.

Hamaker, B.R., A.W. Kirleis, L.G. Butler, J.D. Axtell, and E.T. Mertz. 1987. Improving the in vitro protein digestibility of sorghum with reducing agents. Proc. Nat. Acad. Sci. USA 84:626–628.

Hancock, J.D., P.J. Bramel-Cox, K.R. Smith, B.J. Healy, C.F. Kloppenstein, and M.D. Witt. 1990. Selection for increased in vitro digestibility improves the feeding value of sorghum grain. J. Anim Sci. 90(Suppl. 1):320.

Hulan, H.W., and F.G. Proudfoot. 1982. Nutritive value of sorghum grain for broiler chickens. Can. J. Anim. Sci. 62:869–875.

Mohan, D.P. 1975. Chemically induced high-lysine mutants in *Sorghum bicolor* (L.) Moench. Ph.D. thesis. Purdue Univ., West Lafayette, IN.

National Research Council. 1994. Nutrient requirements of poultry. 9th ed. National Academy Press, Washington, DC.

Oria, M.P., B.R. Hamaker, and J.D. Axtell. 2000. A highly digestible sorghum cultivar exhibits a unique folded structure of endosperm protein bodies. Proc. Natl. Acad. Sci. USA 97:5065–5070.

Oria, M.P., B.R. Hamaker, and J.M. Shull. 1995a. In vitro protein digestibility of developing and mature sorghum grain in relation to α-, β-, and γ-kafirins disulfide crosslinking. J. Cereal Sci. 22:85–93.

Oria, M.P., B.R. Hamaker, and J.M. Shull. 1995b. Resistance of sorghum α-, β-, and γ-kafirins to pepsine digestion. J. Agric. Food Chem. 43:2148–2152.

Paarlberg, D., and P. Paarlberg. 2000. The agricultural revolution of the 20th century. Iowa State Univ. Press, Ames, IA.

Pesti, G.M., and B.R. Miller. 1993. Animal feed formulation. Economic and computer applications. An AVI book published by Van Nostrand Reinhold, New York.

Rostagno, H.S., H.R. Featherson, and J.C. Rogler. 1973. Studies on the nutritional value of bird resistant sorghum grain for chicks: I. Growth studies. Poult. Sci. 52:765–772.

Schnell Publishing Company. 1975–1997. Chemical marketing reporter. Vol. 207–251. Schnell Publ. Co., New York.

U.S. Department of Agriculture, Economic Research Service. 1999. Feed situation and outlook yearbook. April. USDA-ERS, Washington, DC.

U.S. Department of Agriculture, Economic Research Service. 2000. Livestock, dairy and poultry: Situation and outlook. LDP-M-78. December 27. USDA-ERS, Washington, DC.

U.S. Department of Agriculture, Economic Research Service. 2001a. U.S. and regional grain sorghum (milo) production costs and returns per planted acre: 1997–98 [Online]. Available at http://www.ers.usda.gov (verified 6 June 2002). USDA-ERS, Washington, DC.

U.S. Department of Agriculture, Economic Research Service. 2001b. World agricultural supply and demand estimates. WASDE-371. February 8. USDA-ERS, Washington, DC.

Waugh, F.V. 1951. Minimum cost dairy feed. J. Farm Econ. 33:299–310.

Weaver, C.A., B.R. Hamaker, and J.D. Axtell. 1998. Discovery of grain plasm with high uncooked and cooked in vitro protein digestibilities. Cereal Chem. 75:665–670.