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ECONOMICALLY OPTIMAL DISTILLER'S GRAIN
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ECONOMICALLY OPTIMAL DISTILLER'S GRAIN INCLUSION RATES IN BEEF FEEDLOT RATIONS

By

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ABSTRACT

ECONOMICALLY OPTIMAL DISTILLER'S GRAIN INCLUSION RATES IN BEEF FEEDLOT RATIONS

By

Crystal L. Jones

With the rapid expansion of the ethanol industry and rising corn prices, future feed costs are an increasing concern for many feedlot operations. While distiller's grains have the potential to serve as a partial feed substitute, questions remain regarding the degree of economic substitutability between these two feed sources. The purpose of this study is to identify the economically optimal type and inclusion rate of distiller's grains in beef feedlot rations, considering an array of often omitted factors. Most currently prevailing recommendation rates are strictly biologically based and frequently reference only one feeding trial. Unique economic factors considered in this research include the impact of by-product inclusion rates on animal performance (utilizing a meta-analysis of relevant feeding trials) and manure disposal costs, examined under a range of price scenarios. Results indicate the importance of taking these unique factors into consideration when identifying optimal distiller's grain inclusion rates.

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KEY TO SYMBOLS AND ABBREVIATIONS

Symbol / Abbreviation	Definition
AC_{mcr}	Acres - of crop 'c', categorized under application rate 'r', located within mileage category 'm'
ADG	Average Daily Gain (lbs/day)
AG_{mcr}	Allowable Gallons of Manure Application - for crop 'c' , categorized under application rate 'r', located within mileage category 'm'
A_{ji}	Amount of Nutrient 'j' in Feed Ingredient 'i'
b	Incorporation Time (hrs/acre)
Ca	Calcium
C_{cp}	Concentration of Crude Protein in Diet
CDS	Condensed Distiller's Solubles
CGF	Corn Gluten Feed
C_{fs}	Purchase Cost of the Feeder Steer ($)
C_p	Concentration of Phosphorus in Diet
CP_i	Concentration of Crude Protein in Feed Ingredient 'i'
CV	Coefficient of Variation
DC	Disposal Cost ($/hr)
DDG	Dried Distiller's Grains
DDGS	Dried Distiller's Grains with Solubles
DG	Distiller's Grains
DGS	Distiller's Grains with Solubles
DM	Dry Matter
DMD	Dry Matter Digestibility (%)
DMI	Dry Matter Intake (lbs DM/day)
DOF	Number of Days on Feed
D_r	Nutrient Density of Manure (lbs/gal)
f.a.	Finished Animal
F/G	Feed to Gain (DMI/ADG)
FC	Feed Costs ($/finished animal)
h	Number of Head
HCW	Hot Carcass Weight (lbs)
I	Interest Rate Charges ($/year)
i	Daily Interest Rate ($/day)
IT	Total Incorporation Time (hrs)

Key to Symbols and Abbreviations (cont'd)

Symbol or Abbreviation	Definition
K	Fixed Costs ($/finished animal)
K_j	Amount of Nutrient 'j' Limited/Required within the Diet
L	Total Number of Loads
L_{mcr}	Number of Loads - going to crop 'c', categorized under application rate 'r', located within mileage category 'm'
LP	Linear Programming
LT	Total Loading Time (hrs)
lt	Loading Time (hrs/load)
MDC	Manure Disposal Costs ($/finished animal)
MDGS	Modified Distiller's Grains with Solubles
M_m	Miles within Mileage Category 'm'
N_e	Total Nitrogen Excreted (grams of DM/operation)
OLS	Ordinary Least Squares
P	Phosphorus
P_{corn}	Price of corn
P_{cs}	Price of corn silage
P_e	Total Phosphorus Excreted (grams DM/operation)
P_i	Concentration of Phosphorus within Feed Ingredient 'i'
ppm	Parts per Million
P_y	Output Price ($/lb)
Q	Measure of Carcass Quality
R	Revenue ($/finished animal)
RR_{cr}	Nutrient Removal Rate (lbs/acre)
S	Solids Excreted in the Manure (%)
SR	Hours Required to Travel One Mile: Empty Load
SRW	Standard Reference Weight (kg for Choice ~28% marbling)
ST	Hours Required to Travel One Mile: Full Load
SUR	Seemingly Unrelated Regression
SW	Starting Weight (lbs)
TM	Total Manure Excreted (grams DM/operation)
ts	Tank Size (gallons)
TT	Total Transportation Time (hrs)
UT	Total Unloading Time (hrs)
VC	Other Variable Costs ($/finished animal)
V_i	Cost of Feed Ingredient 'i' in Ration ($/lb DM)
VN	Value of the Nutrients in the Manure ($/lb)
WDG	Wet Distiller's Grains
WDGS	Wet Distiller's Grains with Solubles

Key to Symbols and Abbreviations (cont'd)

Symbol or Abbreviation	Definition
X_i	Concentration of Feed Ingredient 'i' in Ration
Y	Finished Weight (lbs)
YC	Yardage Costs ($/day)
Z	Other Manure Disposal Cost Variables
π	Profit ($/finished animal)

CHAPTER 1: INTRODUCTION

(1.1) Problem Statement

In recent years the U.S. has placed growing importance on the pursuit of bio-based fuel sources, driven by mounting concerns regarding dependency on foreign oil and the state of our future resources. As a result, the ethanol industry has experienced rapid growth over the last few decades. According to the Renewable Fuels Association (RFA 2007), a record 4.9 billion gallons of ethanol was produced in 2006, a 300% increase over production in 2000. The RFA (2007) also noted that with the construction and expansion of ethanol facilities underway in 2006, an additional 6 billion gallons of production capacity can be expected to be added by 2009. In fact a recent study projects ethanol production from corn to reach 14.8 billion gallons by 2011 (Tokgoz, et al. 2007).

This rapid expansion of ethanol production across the country has many economic ramifications that reach beyond the direct effects on the fuel economy, state revenues, and employment opportunities. One growing concern of livestock and poultry producers is the effect that this growing ethanol market has on feed costs. Corn, an important feed source for many animal industries, is commonly used as the primary input in U.S. ethanol production. As the demand for corn increases, livestock and poultry producers become increasingly concerned about rising feed costs.

The amount of corn utilized in the production of ethanol has increased significantly over the last few decades (figure A), reaching 1.8 billion bushels in 2006, or 17% of total U.S. corn production (RFA 2007). As a result of this increasing corn demand, upward pressure on corn prices is felt by many livestock and poultry producers.

A recent study conducted by McNew and Griffith (2005) evaluated the impact of new ethanol facilities on local grain prices and found that on average there was a 12.5 cent per bushel increase in the price of corn at the ethanol plant, while a positive price response was shown up to 68 miles from the plant. Additionally, a recent Center for Agricultural and Rural Development (CARD) study projects a 94 million acre increase in corn acreage and a resulting season-average corn price of $3.40/bu by the year 2011 (Tokgoz, et al. 2007).

While the expansion of the ethanol industry is likely to continue, uncertainty regarding exact production levels can be expected to persist. Likewise, the future of the corn industry and questions concerning future corn prices are still uncertain. This uncertainty within the ethanol and corn markets, combined with current corn prices, is causing many livestock and poultry producers to be concerned about their future feed costs. According to the CARD report, an eventual decline in livestock production can be expected, allowing higher feed prices to be passed on to consumers (Tokgoz, et al. 2007). The report concludes that U.S. food prices would increase by a minimum of 1.1% over baseline levels (Tokgoz, et al. 2007).

However, a possible alleviation to this uncertainty may come in the form of distiller's grains. The by-product of ethanol production, distiller's grains (DG), can be incorporated into livestock and poultry rations as a partial substitute for the corn, soybean meal, and urea currently being fed. For every bushel of corn approximately 2.8 gallons of ethanol and 17 pounds of distiller's grains are produced (RFA 2007). Two key questions are then raised in regard to future feed costs. First, "what extent can distiller's grains serve as a substitute for corn in feed rations?" and secondly, "what will happen to future distiller's grain prices?" This latter question has a lot to do with the first. Some individuals speculate that DG production will increase more rapidly than demand, causing DG prices to decrease. Others argue that distiller's grains can be expected to remain competitively priced with corn, or even possibly increase relative to corn prices. This leads to one core question, "what is the demand for distiller's grains?"

Given the relative novelty of distiller's grains to the feed industry, determining its demand poses many challenges. Standard demand estimation is fronted by numerous data issues, complicated further by a general lack of understanding as to the merits of this "new" feed source. While DG consumption data is largely unavailable and available price data is limited in depth, especially in comparison to the staple commodities which have been well established within the feed industry for many years, the fundamental forces driving its demand remain the same. Producers can still be expected to operate in such a way as to maximize operational profits. Therefore, one particular determinant of DG demand is, and will continue to be, the economic substitutability between corn and distiller's grains.

There have been numerous nutritional investigations that have explored the impact of alternative DG inclusion rates within various livestock and poultry rations (including a limited number of economic analyses) relative to corn. Nevertheless, a more comprehensive approach that encompasses the range of important results identified within this body of literature is needed to better identify the substitutability between distiller's grains and corn. Once this question is answered, one can return to the questions regarding distiller's grain demand and expected feed costs.

(1.2) Scope

The focus throughout this thesis will be on the substitutability between corn and distiller's grains in beef feedlot rations. While other tradeoffs, such as the tradeoff between DG and soybean meal exist, they will not be considered within the scope of this thesis. Additionally, beef was chosen due to the fact that the beef industry is considered by industry experts to be the leading animal industry in terms of its utilization potential for this alternative feed ingredient (on a percent dry matter fed basis). The beef industry also accounted for 42% of the total quantity of distiller's grains consumed in 2006, which was a 5% increase from 2005 (RFA 2007). This was the 2nd highest consumption rate, following consumption by the dairy industry.

By focusing on the feedlot segment of the beef industry, a segment with a relatively high feed intake in terms of total dry matter consumed per day is considered. Henceforth, the percent of distiller's grains that can be included in the ration will have a larger impact on the total amount of distiller's grains consumed relative to other livestock industries (e.g. swine or poultry) or other beef industry segments (e.g. cow-calf). Additionally, there is more information currently available regarding how finishing cattle respond, biologically, to the inclusion of distiller's grains than animals from other segments of the beef industry. This segment also faces potentially fewer challenges with regards to the transport, storage, and handling of distiller's grains than other segments. This is in large part attributable to the larger size of the typical feedlot operation, as well as their greater access to financial resources. Access to financial resources becomes a factor as the operation may need to make adjustments to accommodate new ration formulations, such as the purchase of new storage facilities required to store increased levels of distiller's grains.

(1.3) Organization of Thesis

The remainder of this thesis is organized as follows. First, a general overview of the literature pertaining to this topic will be presented, followed by the identification of current gaps in the research. Then, the objectives of the research presented within this thesis will be outlined, followed by the conceptual framework, methodology and data, and finally, the research results, sensitivity analysis, and conclusions.

CHAPTER 2: LITERATURE REVIEW

There are many factors, both biological and economic, that play a role in determining the optimal inclusion of distiller's grains into beef feedlot diets. This section provides a general overview of the literature regarding this discussion of optimal distiller's grain inclusion rates. First, a general description of the by-product production process will be presented, along with a description of the variety of distiller by-product types. Then, the nutrient composition values for distiller's grains will be discussed, followed by a synopsis of the literature addressing how the inclusion of distiller's grains affects finishing cattle performance relative to a base corn diet. Subsequently, an economic discussion is provided; covering topics such as feed prices, transportation, storage, manure management, and the reliability of supply and nutrient content. Finally, the discussion will move away from the incorporation of distiller's grains. Given that the proposed research problem aims to identify the economic substitutability between this 'new' grain source and corn, an overview of the evolution and objectives of various economic ration formulation methods will be outlined.

(2.1) General Information on Distiller's Grains

(2.1.1) By-Product Production Processes

A large part of what affects the degree of substitutability between distiller's by-products and other feed sources is its nutrient content relative to these other feeds. To begin, it is important to note that when talking about the nutrient content of distiller's grains, one must first specify the type of by-product in reference.

There are two main types of fermentation processes: dry milling and wet milling. Wet milling processes produce by-products known as gluten products, such as corn gluten feed and corn gluten meal. While the ethanol dry milling process, which is the focus of this paper, produces distiller's grains (DG). (Stock, et al. 2000)

There are various types of distiller's grains that can be produced from the dry milling process. During the ethanol production process the source grain (typically corn) is ground and the starch is fermented. The grain particles are then separated from the liquid and can be sold as either wet distiller's grains (WDG), which are typically about 30% dry matter (DM), or dry distiller's grains (DDG), consisting of approximately 90% DM. When the by-product is sold as either WDG or DDG, the liquid fraction can then be evaporated; producing a by-product known as condensed distiller's solubles (CDS). Another option is to mix the CDS with the WDG to produce wet distiller's grains with solubles (WDGS) or it may be dried with the DDG to produce dried distiller's grains with solubles (DDGS). (Stock, et al. 2000)

While other types of distiller's grains exist, such as modified distiller's grains with solubles (MDGS), which are approximately 50% DM, a survey recently conducted by the National Agricultural Statistics Service (NASS 2007) reported that wet and dry distiller's grains with solubles were among the more common types of co-products used by "cattle on feed". For this reason, these two DGS types will remain the primary focus of this thesis.

Many ethanol facilities are set-up for DDGS production; however, due to the additional cost of the natural gas required to dry the by-product, producing and selling WDGS may be a preferred marketing option for plants with sufficient WDGS demand.

On the other hand, DDGS are easier and less costly to transport and can be stored for longer periods of time without molding or freezing as quickly as WDGS. Therefore, for plants that transport a large portion of their by-product or which face large unreliable fluctuations in distiller's grain demand throughout the year and require greater quantities of storage for their by-product, DDGS may be the preferred marketing option. Regardless of the plant's decision, the type of distiller's grain produced has no effect on the ethanol production process, as the drying process occurs entirely after the ethanol production process has been initiated.

(2.1.2) Nutrient Composition of Distiller's Grains

The nutrient composition of distiller's grains with solubles (DGS), a category that includes both wet and dry distiller's grains, is generally three times the composition of the grain source used in ethanol production. This is because most grains contain approximately 2/3 starch, which is removed during ethanol production, leaving the resulting by-product with a nutrient density three times that of the original grain (Kononoff and Erickson 2006). Keeping this fact in mind, distiller's grains with solubles (where the source grain is corn) are considered to be a good source of ruminally undegradable protein, energy, and readily digestible fiber (Schingoethe 2006). However, this also means that they tend to be high in fat (Stock, et al. 2000), sulfur, and phosphorus; the implications of which will be discussed in succeeding sections of this chapter.

Distiller's grain nutrient composition values found within the literature are typically cited from one of the National Research Council's (NRC) Nutrient Requirement publications (e.g *Nutrient Requirements of Beef Cattle, 1996 and Nutrient Requirements of Dairy, 2001)*. However, given that many of the ethanol processing technologies have changed since many of these values were collected, there have been efforts by researchers to collect updated nutrient content data (Spiehs, et al. 2002; University of Minnesota 2006; Belyea, et al. 2004). Table 1 compares the nutrient composition values of DDGS as reported from these various sources[1].

Given that the nutrient content within DGS depends largely on the source grain, the processing plant and differences in types of yeast, fermentation and distillation efficiencies, as well as the amount of solubles blended back into the grain (Tjardes and Wright 2002); the importance of testing becomes paramount. This point is further emphasized given that research by the University of Minnesota (2006) and Spiehs, et al. (2002) has revealed significant variation in nutrient content both within and across ethanol facilities. These values are included as coefficients of variation (CV) within the above referenced nutrient composition table (table 1).

(2.2) Feeding Distiller's Grains – Animal Science Perspective

(2.2.1) Effect of Distiller's Grains with Solubles on Finishing Cattle Performance

Given the potential of distiller's grains to serve as a relatively low cost feed source, there has been a great deal of literature published aimed at establishing feeding guidelines for distiller's grains. Over the years, there have been many nutritional studies conducted which have assessed the impact of various DGS inclusion levels on animal performance and carcass quality. In general, most of these trials report that feeding

[1] While values are only provided for DDGS, the nutrient composition of WDGS grains are theoretically similar on a percent DM basis.

distiller's grains result in net energy values greater than corn. However, a great deal of subsequent discussion has focused on the type and inclusion level of the distiller's grain in reference: wet or dry; with or without solubles, along with the degree and significance of the reported net energy differences.

With the exception of a few discrepancies within the literature (e.g. Schingoethe 2006), it appears that the energy value of distiller's grains without solubles is similar to corn, and that the reported energy difference between corn and distiller's grains is due to the solubles portion of the feed (Loy and Miller 2002). However, it is worth noting that phosphorous, sulfur, and fat content also increase with the addition of solubles (Schingoethe 2006).

Given that several feeding trials have shown that feeding distiller's grains with solubles result in higher energy values relative to corn, further research has explored differences in animal performance when fed WDGS versus DDGS. Several of the feedlot research trials evaluating animal performance in relation to distiller's grain inclusion have tended to favor wet distiller's over dry, showing that wet distiller's resulted in greater increases in feed efficiency (Loy and Miller 2002). A few authors that have conducted feeding trials since 1990 which enable a direct comparison between WDGS and DDGS include: Ham, et al. 1994a; Lodge, et al. 1995; Trenkle 1996; Mateo, et al. 2004; and Cole, et al. 2006. All of these cited trials conclude that, on average, animals fed WDGS had a lower feed to gain ratios than those fed DDGS. Possible reasons given by Loy and Miller (2002) include: moisture content, a reduction in subacute acidosis in cattle, and heat damage during the drying process.

While Klopfenstein (1991) confirms that lower energy values are found within *severely* heat damaged distiller's grains, it is acknowledged that this extreme situation rarely occurs. As a follow-up, Klopfenstein (1996) and Ham, et al. (1994b) both conducted studies that showed that WDGS did in fact have higher energy values than DDGS and that the acid detergent insoluble nitrogen (ADIN)[2] concentration level of the fed DDGS did not significantly affect performance.

As a continuation of this dry versus wet discussion, Trenkle (1997) conducted a study to determine the effects of switching a diet from wet to dry. This study concluded that if intake is managed during this transition, these two feeds can be successfully switched without sacrificing animal performance.

Meta-Analysis

In an effort to gain perspective regarding the numerous studies examining the impact of DGS inclusion on animal performance and carcass quality, Dr. Steven Rust, beef nutritionist at Michigan State University, collected data from 17 yearling feeding trials conducted since 1990[3] with WDGS and/or DDGS treatments. Only those studies which included a control (a corn based diet with no distiller's grains) and which explicitly stated they were using distiller's grains with solubles were included within the analysis. Average daily gain (ADG), dry matter intake (DMI), feed to gain (F/G), and marbling data reported from these trials are shown within table 2, and will be referenced by trial number throughout the remainder of this thesis.

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[2] ADIN is a measure of heat damage.
[3] Only trials conducted since 1990 were used in order to reduce any possible effect older technologies may have on results.

Inferences regarding the impact of DGS inclusion on animal performance (ADG, DMI, and F/G) vary significantly across trials. Figures B1-D1 and B2-D2 illustrate this variability across feeding trials by plotting DDGS (1) and WDGS (2) inclusion levels, respectively, against F/G (B), ADG (C), and DMI (D), respectively. Note that very few trials examined both WDGS and DDGS, which would allow for direct comparison under a controlled experiment environment. This was done only by trials 13-17.

When figure B1 is examined, we see that increasing DDGS inclusion has a rather ambiguous impact on F/G, consistent with the ambiguity seen within the ADG and DMI response figures (C1 and D1, respectively). For some DDGS trials a positive relationship is found between feed efficiency and DDGS inclusion level, and for others either a negative relationship or no relationship is suggested. For example, Buckner, et al. (2007b) observed a quadratic trend for ADG, no affect on DMI, and linearly decreasing F/G when DDGS inclusion levels were increased from 0% to 40% (trial #11). In contrast, Mateo, et al. (2004) concluded that increasing DDGS inclusion from 0% to 40% had no affect on ADG, a positive affect on DMI, and a slightly positive impact on F/G (trial #16).

On the other hand, as shown in figure B2, general downward trends in F/G ratios *were* observed across WDGS feeding trials, despite the ambiguity surrounding the degree and significance of its impact. This same conclusion is made by multiple authors represented within table 1. For example, Larson, et al. (1993) found a linearly decreasing relationship between WDGS inclusion and F/G, concluding WDGS inclusion resulted in increased feed efficiency (trial #1). Likewise, Trenkle (1996) found that steers fed WDGS increased feed efficiency by 9% over the base corn diet (trial #17).

Despite the general downward trend between WDGS inclusion and feed to gain, ambiguity across trials still exists regarding the functional form for ADG and DMI response functions. For example, Vander Pol, et al. (2006a) found a statistically significant quadratic relationship between WDGS inclusion and both ADG and DMI (trial # 10). Loza, et al. (2005) also found evidence of statistically significant quadratic relationships between WDGS inclusion and both ADG and DMI; however, their rations were blended with corn gluten feed as well, making it difficult to isolate the effects of WDGS inclusion level (trial #4). However, while both Loza, et al. (2005) and Vander Pol, et al. (2006a) found evidence of statistically significant quadratic relationships between WDGS inclusion and both ADG and DMI, results from Trenkle (1996) are less supportive of this strong quadratic relationship (trial #17).

An additional question that has been raised is how the inclusion of distiller's grains impacts carcass quality. A subset of the trials within the meta-analysis report measures of carcass quality, more specifically they report marbling scores (figures E1 and E2). As with the feed to gain discussion above, dietary effects on marbling are not entirely conclusive. However, the majority of these studies concluded that DGS inclusion does not have a significant affect on carcass quality.

Vander Pol, et al. (2006a) found the only significant carcass quality difference to be hot carcass weight (HCW), where increasing WDGS inclusion from 0% to 30% increased HCW from 777 lbs to 827 lbs and then further inclusion, up until 50%, decreased HCW back down to 796 lbs (trial #3). The study found no significant differences for any of the other observed carcass characteristics, which included: liver score, rib fat, ribeye area, marbling score, and yield grade (Vander Pol, et al. 2006a).

Likewise, Buckner, et al. (2007b) found that increasing the DDGS inclusion level did not impact any carcass characteristic (other than HCW), where measured characteristics included: marbling score, ribeye area, rib fat, and calculated yield grade (trial #11). Additionally, Trenkle (1996) also concluded that there were no differences among treatment diets and dressing percentage, ribeye area, or quality grades. However, Trenkle (1996) did note that increasing WDGS inclusion levels resulted in lower yield grades, greater fat thickness, and more kidney-heart-pelvic fat.

(2.2.2) Feeding Recommendations

This large breadth of research on the effect of including distiller's grains on animal performance has led to various maximum DGS inclusion recommendations. While the exact recommendation rate varies slightly throughout the literature, a commonly reported limit for DGS inclusion within feedlot diets is between 30 and 40 percent (Benson, et al. 2005; Buckner, et al. 2007a; Tjardes and Wright 2002; Lardy 2003; Vander Pol, et al. 2006a).

Regardless of the exact recommendation for DGS inclusion, several key feeding guidelines have been emphasized by beef nutritionists. Given that distiller's grains with solubles are high in phosphorus and low in calcium, many nutritionists point out the importance of watching the calcium (Ca) to phosphorous (P) ratio, in order to avoid urinary calculi (Tjardes and Wright 2002). According to Tjardes and Wright (2002), Ca to P ratios should be greater than 1.2:1 and less than 7:1. Additionally, given that sulfur levels exceeding 0.40% of daily dry matter intake can lead to poliocenphalomalacia (Sexten 2006; Tjardes and Wright 2002) and distiller's grains are high in sulfur, it is important to monitor sulfur intake. This is particularly true in areas with high levels of sulfur content in the animal's drinking water.

(2.3) Feeding Distiller's Grains – Economic Perspective

The majority of the economic research on the effects of ethanol expansion has focused on corn price effects, ethanol profitability, employment impacts, and the effect on linked industries (both upstream and downstream). As outlined within the introduction, the expansion of the ethanol industry is expected to continue placing upward pressure on corn prices, leading researchers such as Tokgoz, et al. (2007) to conclude that livestock production will eventually decline in order to pass the effect of rising feed costs on to consumers. This conclusion assumes that the price of distiller's grains will remain highly correlated with the price of corn. While this may be true, the spread will be largely determined by its demand relative to supply. This is where further insight into how corn and distiller's grains are economically substitutable will contribute to the discussion regarding the impact of ethanol expansion on livestock markets, such as the beef feedlot industry.

(2.3.1) Economic Factors

There are a variety of economic considerations that have been addressed within the literature pertaining to the determination of appropriate distiller's grain inclusion levels. In addition to the price of the grain and competing feeds; reliable supply, storage, transportation, and waste management factors must also be taken into account.

Reliable Supply

Loy, et al. (2005) point out that ration consistency is very important to feedlot operations due to the fact that cattle are managed for fast growth and efficiency, and that a consistent ration reduces digestive upsets. Additionally, producers consider nutrient variability when formulating their rations because they want to be assured that basic nutritional requirements are met and that certain nutritional limits are not exceeded. As seen within the table 1, the nutrient content of distiller's grains can be highly variable. Such variability will directly impact the appropriate DGS inclusion rate when nutritional requirements/limits are of concern.

Storage

Storage considerations also have the potential to impact feeding decisions where distiller's grains are being incorporated. Wet distiller's grains can freeze in the winter and mold in the summer. The typical shelf life for wet distiller's grains in warmer weather is about 7 days; however, when kept in silage bags they have been successfully stored for more than 6 months (Tjardes and Wright 2002). Dry distiller's grains on the other hand are easier to store, as they have a lower moisture content, and do not mold as easily; however, wind may be a factor due to the small particle sizes (Tjardes and Wright 2002).

Transportation

As with most feed decisions, transportation costs must be incorporated into total feed cost calculations. The distance to the nearest ethanol plant or distiller's grain source compared to the corn source is important to a feedlot operator deciding which feeds to include in their rations and in identifying optimal inclusion levels. However, even at equal distances, moisture differences between these feeds will cause variation in their respective transport costs. For instance, WDGS have a high moisture content relative to both DDGS and to corn; therefore, transportation costs associated with WDGS are higher on a dry matter basis (Vander Pol, et al. 2006b).

Manure Disposal

As mentioned earlier, the high phosphorous content in distiller's grains make manure disposal costs an important consideration when determining optimal DGS inclusion rates. By managing the total quantity of manure excreted as well as the nutrient density of the manure, overall profits may be impacted through reduced storage needs and by decreasing the acreage required for manure application (Powers and Van Horn 1998). Given that Tomlinson, et al. (1996) and Morse, et al. (1992) note variation in nutrient intake as the single most important contributor to overall variation in nutrient excretion, changes in dietary nutrient intake levels will directly impact the amount of nutrient excreted in the manure. Therefore, distiller's grains which are high in both crude protein and phosphorus will directly impact the amount of nitrogen and phosphorus excreted in the manure, thereby impacting manure management costs.

Several feeding studies have evaluated phosphorus and nitrogen excretion levels under a variety of DGS inclusion levels. For example, Benson, et al. (2005) collected phosphorus excretion levels and found that phosphorus excretion increased by 453 ppm as the DDGS inclusion rate was increased from 0% to 35% (table 3a). Meyer, et al. (2006) also collected phosphorus excretion levels under various DGS inclusion rates; however, their evaluated diet contained between 0% and 20% WDGS. Their results, shown in table 3b, show that phosphorus excretion levels increased from 13.2 grams per day to 19 grams per day. Additionally, an Iowa State University study estimated excretion rates for both nitrogen and phosphorus at various DDGS inclusion rates using a software program where feed consumed per day was assumed to be 22.8 lbs and the number of days on feed was assumed to be 152 (table 3c; Powers, et al. 2006). Each of these studies provide evidence of elevated phosphorus and/or nitrogen excretion resulting from increased DGS inclusion levels.

While these reports serve as a good reference, the nutrient composition of feed ingredients vary across diets, as well as the percentage of each feed ingredient included within the diet. Therefore, nutrient intake will vary from the above referenced trials, limiting the appropriate use of these tables for predicting nutrient excretion levels. For these reasons, Powers (2002) recommended that the previous American Society of Agricultural Engineer (ASAE) publication ASAE Standard D384.1 (1994), which included tables of typical manure excretion composition and quantity levels, be updated to make nutrient excretion a function of dietary intake. The ASAE Standard D384.2 (2005), *Manure Production and Characteristics,* now incorporates such excretion functions, where manure excretion composition and quantity can be calculated given dietary intake, dry matter intake, and weight information.

(2.3.2) Identifying Economically Optimal Distiller Grain Inclusion Levels

In order to incorporate some of the above mentioned economic considerations into DGS inclusion recommendations, Vander Pol, et al. (2006b) conducted an economic analysis of feeding WDGS in feedlots using animal performance information, feed prices, transportation costs, and yardage costs at five dietary inclusion levels. Using eleven published research trials, the authors formulated an energy function where energy value relative to corn (y) was a function of the percent of WDGS included within the diet (x) $y = 164.2 - 0.84x; R^2 = 0.28$ [4]. Then, a published control value from Vander Pol, et al. (2006a) and energy values at various inclusion levels calculated from the energy equation above were used to calculate adjusted feed efficiency values. Next, using their own research trial, the authors formulated a statistically significant quadratic average daily gain response equation: $a = 3.66 + 0.04x - 0.0007x^2; R^2 = 0.91$, where a indicates predicted average daily gain (Vander Pol, et al. 2006a). ADG estimations at each DGS inclusion level were then divided by the adjusted feed efficiency values to calculate DMI. (Vander Pol, et al. 2006b)

In their economic analysis, Vander Pol, et al. (2006b) held finished weight constant and adjusted days on feed to reflect the number of days it would take to achieve the same weight as a typical feedlot animal fed 0% WDGS for 153 days. Trucking costs

[4] All variables within this reported energy equation are assumed to be significant; although, not directly stated within the referenced Vander Pol et al. (2006b) article.

were quoted at $2.50/loaded mile (load = 25 tons), and they increased the yardage costs per head for cattle fed WDGS to account for the increased equipment, labor, and fuel costs associated with this high moisture feed. To calculate this increased cost, the percentage increase in WDGS inclusion was multiplied by the control yardage cost of $13.00 per finished animal. (Vander Pol, et al, 2006b)

The economically optimal WDGS inclusion rate was then calculated for feedlot operations located within 0, 30, 60, and 100 miles from the ethanol facility under three different corn price scenarios. Vander Pol, et al. (2006b) conclude that 40% WDGS can economically be fed for operations located up to 100 miles away from the plant.

(2.4) Overview of Economic Ration Formulation Models

One common approach to economic ration formulation modeling is through the use of linear programming (LP), a method which has frequently been used since it was first introduced by Waugh in 1951 (e.g. Allison and Baird 1974; Williams and Ladd 1977; Black and Hlubik 1980; Appland 1985; LaFrance and Watts 1986; Polimeno, et al. 1999; and Coffey 2001). LP ration formulation models are typically used to minimize feed costs subject to a specified performance level and a set of nutritional requirements. However, various modifications have been applied to this "traditional" ration formulation technique, which has eventually led to more complex non-linear mathematical optimization models.

One of the first critiques of "traditional" linear programming as a ration formulation tool is the impracticality of holding the target performance level constant. LP assumes that the same productivity per unit of a ration results regardless of ingredient sources (Allison and Baird 1974). However, the ration itself and the quality of the ingredients within the ration directly impact both animal growth rates and carcass quality characteristics. While an LP model may be successful in finding the least cost ration for a particular period of time, failing to consider how the ration will affect animal growth rates may result in an increased number of days required to reach a specified finished weight. This will cause total feed costs, yardage costs, and interest costs to increase. Additionally, just as animal growth rates may be affected by ration ingredients, so may carcass quality characteristics, which can potentially result in price premiums or discounts at the time when the animal is sold.

The impracticality of holding target performance levels constant has been addressed through various methods. For example, Allison and Baird (1974), Appland (1985), Miller, et al. (1986), Costa, et al. (2001), and Boys, et al. (2007) have sought to address the impracticality of assuming constant productivity across rations, while Li (2003) and Forsberg and Guttormsen (2006) have sought to address the carcass quality issues.

Allison and Baird (1974) and Appland (1985) both modified the "traditional" linear programming model to incorporate animal growth response. Allison and Baird (1974) utilized a linear programming model, allowing for a multitude of ration combinations to be chosen. Data on the relationship between feed conversion and animal growth rates with crude protein and energy levels were available for two growth stages (1974). The protein content of each ration was then used to determine the growth rate and feed conversion ratios utilized within the model; thereby, "determining the least-cost rations rather than minimizing feed cost per pound of gain…" (1974). Appland (1985) used a grid linearization technique employed within a dynamic linear program to capture the non-linearity introduced when time on feed, optimal end weight, and optimal gain on feed factors were considered. Appland (1985) found that by incorporating these other components, increasing the interest rate shifted the feed ration to a more intensive grain ration, and found the results to be of particular importance to producers with less costly forage rations and high opportunity costs for capital.

Other studies have employed non-linear mathematical programming techniques to address the impracticality of assuming constant productivity across rations, including: Miller, et al (1986), Costa, et al. (2001), and Boys, et al. (2007). While Miller, et al. (1986) used quadratic programming to incorporate production response information into a broiler ration formulation model, Costa, et al. (2001) utilized a two-stage mathematical program to examine the choice between peanut meal vs. soybean meal. Alternatively, having data on animal growth rates at various stages along a production period, allowed Boys, et al. (2007) to develop a non-linear simulation model to determine optimal slaughter weights of pigs. This study was designed to illustrate the importance of taking heterogeneous animal growth rates within a herd into account.

In order to account for the effect a ration can have on output quality; Li, et al. (2003) used a mathematical simulation model to find optimal inclusion rates of Paylean®, a feed additive within swine rations shown to affect growth rates, feed intake, and dressing percentage. Likewise, Forsberg and Guttormsen (2006) also utilized a mathematical programming model to account for quality effects when they looked at economically optimal dietary rations for farmed Atlantic salmon, taking pigmentation effects into consideration.

A second critique of LP ration formulation models is that linear programming assumes the nutrient content of the ration is known. In reality the nutrient content may vary within a diet leading to variation in the growth rate of the animals (Tozer 2000). Two alternative methods, proposed to deal with this uncertainty in the nutrient content of the ration, were examined by Tozer (2000). Tozer (2000) compared the use of stochastic programming with that of employing the safety margin method within a linear programming framework to formulate Holstein heifer rations. Results indicated that stochastic programming allows for better control over the probability of achieving a desired nutrient content within the ration than simply applying the safety margin method to a linear programming model (Tozer 2000).

A third critique, also dealing with uncertainty, was made by Coffey (2001) in regard to feed price uncertainty. Coffey (2001) notes that the variation in feed prices overtime will affect total profit; however, it is also noted that producers prefer a consistent ration. This leads Coffey (2001) to utilize a mean variance framework to select optimal feed rations for a beef backgrounder facing uncertainty in feed ingredient prices.

A fourth critique of LP recognizes that producers may have alternative objectives, other than the sole objective of minimizing feed costs. For this reason, multiple objective (goal) programming models (MOP) have been utilized in a multitude of scenarios (e.g. Rehman and Romero 1984; Lara 1993; Beaudoin, et al. 2002; Jean dit Bailleul, et al. 2001; Tozer and Stokes 2001; and Zhang and Roush 2002; Castrodeza, et al. 2005; Pomar, et al. 2006).

For example, Castrodeza, et al. (2005) used interactive MOP in order to minimize feed costs within swine diets, as well as decrease the amount of phosphorus in the ration.

They first listed a set of objectives and found the optimal ration when each of the objectives was optimized. They then constructed a matrix (P_1) of the objective values under each model run (i.e. when the model was run optimizing objective #1, objective #2,..., objective #N). Then, the decision maker would indicate which of the optimized objectives they preferred to improve first, the model would then be re-run with the new objective goal and a new matrix would be constructed (P_2). Next, the decision maker would evaluate if the improvement in the objective made up for the changes in the other obtainable objective values from P_1. (Castrodeza, et al. 2005)

Pomar, et al. (2006) also used MOP to minimize feed costs while reducing excess phosphorus in the diet. However, rather than utilizing the subjective approach described by Castrodeza, et al. 2005, they followed an approach as discussed by Jean dit Bailleul, et al. in 2001. This approach weights the amount of phosphorus in the diet by β and adds this value to feed costs. Suggested values for β include: a tax on excretion, an excretion treatment cost, or an additional transport cost (Pomar, et al. 2006). This is essentially the approach taken by Hadrich (2007) when manure disposal costs were incorporated into a least cost dairy ration formulation model. Rather than utilizing a MOP model, Hadrich (2007) utilized a linear least-cost formulation model, where the cost of manure disposal was directly incorporated into the cost function. Since this manure cost was not a linear function of dietary inclusion levels, separable programming was utilized to allow for linear approximations of the cost curve (Hadrich 2007).

CHAPTER 3: RESEARCH GAPS AND OBJECTIVES

(3.1) Research Gaps

There are several areas in which our understanding of the optimal inclusion rate of distiller's grains with solubles (DGS) into beef feedlot rations can be enhanced. First, the commonly stated maximum inclusion rate recommendation of 30% to 40% is based largely on nutritional research alone, and does not take many important economic factors into consideration. While break-even analyzes based on these inclusion levels may provide producers with decision rules regarding the break-even price of distiller's at a particular inclusion level, it does not provide any information regarding the appropriate inclusion for DGS given a set of feed prices. Rather than solving for the break-even price given a certain DGS inclusion level, the question to be asked is: what is the optimal DGS inclusion level over a range of prices?

Secondly, most existing economic studies on optimal DGS inclusion rates that incorporate animal response functions (e.g., feed to gain; dry matter intake) focus on a single or a small sample of research trials. As previously noted and illustrated by the meta-analysis trial plots (figures B1 and B2), there is a great deal of variability regarding the degree or even general direction of the relationship between DGS inclusion rates and resulting feed to gain efficiency ratios. Research is needed to account for this uncertainty that currently faces livestock producers regarding animal performance when rations are formulated to utilize DGS. Additionally, traditional methods for estimating these animal response functions have not treated them as a system, where unobservable (or non-recorded) factors which may vary within a trial are likely to influence both ADG and DMI are taken into account.

Thirdly, most studies have focused on the incorporation of either wet or dry distiller's grains. Such an approach does not allow for the profit trade-off between wet distiller's grains with solubles (WDGS) and dry distiller's grains with solubles (DDGS) to be analyzed at various transportation distances. Given that the empirical evidence concludes that there are potential differences in feed efficiency ratios between these two feeds and the fact that WDGS are more costly to transport, an economic trade-off exists for producers between the DGS types available to them.

Fourth, a wide range of price relationships between corn and distiller's grains, as well as between distiller's grain types (WDGS vs. DDGS), have not been fully examined. Most existing research was conducted examining a narrow range of possible feed prices. Additionally, most of this work was done under old, currently irrelevant prices. As the uncertainty regarding the future of the ethanol industry and the corn market causes rising feed cost concerns, a wider set of price scenarios must be examined.

Finally, while nutrient management cost concerns have been addressed throughout the literature, to date, these costs have not been incorporated into an economic study designed to identify the optimal inclusion of DGS into beef feedlot rations. If the nutrient content of the diet directly affects the nutrient concentration of the manure excreted, as stated by ASAE (2005), and DGS are high in phosphorus and crude protein, then the amount of DGS included in the diet will directly impact manure disposal costs. Collectively, these identified research needs have shaped the objectives of this project.

(3.2) Objectives

The purpose of this study is to develop a model in which the economically optimal inclusion rate of distiller's grains (WDGS and DDGS) in beef feedlot rations can be identified in the most appropriate and comprehensive manner currently feasible. The model will be developed taking as many 'traditional' ration formulation model critiques as possible into account (presented within chapter two). This analysis will incorporate standard ration formulation factors such as relative feed ingredient prices, basic nutritional requirements, and mean nutrient composition values. In addition, animal growth rates will be taken into account using non-linear mathematical programming with manure disposal costs directly incorporated into the cost function. Results will then be compared with commonly cited DGS inclusion level recommendations cited within the literature (30% to 40%).

By including animal response functions the trade-off between less efficient feeds, which result in a greater number of days on feed, and more efficient feeds can be compared. As opposed to relying on a single or few feeding trials to determine the relationship between DGS inclusion rates and animal performance, this analysis utilizes the meta-analysis data collected by Dr. Steven Rust. This is particularly important to note given that results from this analysis illustrated significant variation across trials (figures B1-D2); indicating that results from a single feeding trial may significantly bias model results.

Additionally, by accounting for manure disposal costs, the nutrient content of the feed ingredients used within the ration and their impact on manure excretion will be taken into consideration when finding optimal feed rations. For a producer who faces high manure disposal costs, failing to account for how the inclusion of DGS into a ration affects these costs may lead to inclusion rates in excess of the truly economically optimal amount. This study intends to go a step beyond simply saying that increasing DGS inclusion will increase these costs, and asks by how much do these costs increase and does this affect the optimal DGS inclusion level?

Given the nature of such an optimization model, many assumptions are made. Therefore, various sensitivity analyses will be conducted in order to evaluate how changes in key assumptions affect model results. First, the base case model will be established within chapter five. Then, model sensitivity to the following model parameters will be presented within chapter six: feed costs (including transportation, storage, and handling costs), nutrient and feed ingredient constraints, yardage cost and interest rate parameters, manure disposal scenarios, and animal response function estimations.

CHAPTER 4: CONCEPTUAL FRAMEWORK

(4.1) Basic Theoretical Framework

A common behavioral assumption underlying economic theory and applied research states that producers aim to maximize their utility, and a common proxy measure of this utility is profit. While it may be true that other factors influence their decisions, in this analysis maximization of profits is assumed to be each producer's sole goal. Therefore, analyzing how the incorporation of distiller's grains with solubles (DGS) impacts profit maximizing decisions becomes the first step in identifying the economically optimal rate of DGS inclusion into beef feedlot rations. As such, the remainder of this chapter will define the profit function and describe how the inclusion of DGS affects the various components of the function.

(4.2) Defining the Profit Function

In its most simplified form, profit (Π) equals total revenue (R) minus total costs. Equation (1) expands this basic notion, by breaking costs into a few common components inherent to feedlot operations: feed costs (FC), other variable costs (VC), manure disposal costs (MDC), the purchase cost of the feeder steer (C_{fs}), and fixed costs (K). Given that feed ration decisions are affected by more than just feed costs, these other cost and revenue components become important factors of profit maximizing ration formulation decisions. While increasing the amount of a relatively inexpensive feed ingredients incorporated into a diet may lower feed costs, other costs affecting total profit may also be affected. For example, even if DGS are priced below corn (on a dry matter basis), increasing the DGS inclusion rate may not necessarily be economically optimal. Increasing the DGS inclusion rate may also affect yardage costs, incurred interest charges, as well as manure disposal costs. DGS have a high concentration of phosphorus; this will increase MDC by reducing the amount of manure that can be applied per acre, forcing a producer to haul their manure greater distances to dispose of the total quantity of manure produced by the operation. Furthermore, research has indicated that the DGS inclusion level will also affect feed efficiency, thereby impacting both yardage costs and incurred interest charges through its affect on days on feed.

(1) $\Pi = R - FC - VC - MDC - C_{fs} - K$

A more in depth description of each component found within equation (1), along with an examination of how including DGS into the diet affects each component will be discussed in turn.

(4.2.1) Revenue

Revenue equals the price of the output (P_y) multiplied by the quantity of output (Y) (finished weight); allowing for the revenue component within equation (1) to be re-specified as in equation (2). Typically in the feedlot industry, the output price is based on a measure of carcass quality (Q). While there can be many factors that affect this quality, it has been indicated through various research trials that quality may be affected by the inclusion level of DGS in the diet (X_{DGS}). As such, equation (3) specifies price to be a function of diet composition.

(2) $R = P_y Y$

(3) $P_y = g(Q) = g(f(X_{DGS}))$

For all technical purposes, the finished weight is a choice variable. The weight of the animal is easily measurable and observable, and the producer has a choice regarding the final sell weight. However, the number of days on feed (DOF) required for the animal to reach a targeted finish weight (Y) depends on the animal's starting weight (SW) and average daily gain (ADG). The calculation required to obtain Y can now be succinctly expressed as:

(4a) $Y = SW + (ADG * DOF)$

or conversely, to identify DOF we use:

(4b) $DOF = (Y - SW) / ADG$.

However, as previously mentioned, ADG has been found to be affected by the level of DGS included in the diet. Therefore, we allow ADG in equations (4a) and (4b) to be defined generally as:

(5) $ADG = f(X_{DGS})$.

While it is acknowledged that there are many environmental and dietary factors that may impact ADG, the impact of DGS inclusion rates is the primary concern of this study. Furthermore, it is assumed that DGS inclusion does not impact these other factors, and therefore, all other factors can be held constant.

(4.2.2) Feed Costs

The feed cost component of equation (1) can also be further decomposed. Total feed costs to finish a single animal are a summation of the percent of each feed ingredient in the ration (X_i) multiplied by the cost of each feed ingredient (V_i), then multiplied by the estimated quantity of feed consumed per day (DMI), and by the number of DOF .[5] Included in the cost of each feed ingredient (V_i) is the purchase price of the feed, the cost of transporting the feed from its source to the feed bunk, as well as any additional handling and/or storage costs associated with that feed.

Given the aforementioned components of feed costs, this allows feed costs to be defined as:

$$(6)\, FC = [\sum_{i=1}^{n}(X_i V_i)] * DMI * DOF,$$

As with ADG , DMI can be estimated as a function of distiller's grain inclusion, holding all other factors constant. This allows DMI referenced in equation (6) to be generally identified as:

$$(7)\, DMI = f(X_{DGS}).$$

Additionally, it is likely that many of these feed related costs will be a function of firm size. A larger firm may face lower transportation costs per unit than a smaller firm, which may need to organize with other smaller producers in order to facilitate timely transport of the feed. Also, the frequency of DGS transportation needs will likely vary throughout the year due to the effect of weather related changes on storage losses

[5] Various ration formulations may be utilized throughout the total time on feed; however, this has been simplified to only one "average" or "representative" ration. This simplification is due in part to limited information available regarding how finishing cattle respond to various rations incorporating DGS across growth stages.

stemming from molding or freezing. Additionally, the larger firm is more likely to have the resources needed to obtain any additional storage required for the distiller's grains. The larger firm may also have greater access to the feed via more viable contracting options, and thereby, they may also face lower feed prices than the smaller firm.

Furthermore, this feed cost equation is subject to a variety of nutritional constraints which ensure that the animal's nutritional requirements are met and inclusion limits are respected:

$$(8)\sum_{i=1}^{n} A_{ji}X_i \geq (\leq,=)K_j\ ,$$

where; $j = 1,....,m$; $i = 1,....,n,$; X_i is the concentration of feed ingredient 'i' in the diet, A_{ji} is the amount of nutrient j in feed i, and K_j is the amount of nutrient j required or limited within the diet. While a complete list of nutritional requirements and constraints may be quite extensive, these requirements can be limited to only those which are affected by the decision of whether or not to include DGS or which are found to be typically constraining.

(4.2.3) Other Variable Costs

The other variable cost (VC) component of profit (equation 1) includes the accumulation of yardage costs (YC) and interest charges (I) accrued from any operational loan the producer may have, across the time the animal is on feed (equation 9). Here, the operation's interest charges are calculated by taking the daily interest rate (i) multiplied by the operational loan, multiplied by the number of days the animal is on feed. A common approach used to estimate a feedlot's typical operational loan per head is to use the sum of the purchase cost per feeder steer and half of its anticipated feed costs. This leads VC to be identified as:

$$(9)\, VC = (YC + I) * DOF = [YC + i * (C_{fs} + 0.5 * FC)] * DOF \,.$$

Other costs, typically considered variable costs within the industry (e.g. health costs) are assumed to be unaffected by the inclusion of distiller's grains into the ration, and are therefore not included within this "other variable cost" component of the profit function.

(4.2.4) Manure Disposal Costs

Manure disposal costs (MDC), per head, are a function of not only the total quantity of manure excreted (TM) by the operation and its nutrient density (in terms of total grams of phosphorus (P_e) and nitrogen (N_e) excreted per gallon of manure), but other factors (Z) as well. These other factors may include the type of crops available for manure application, the nutrient requirements of these crops, the nutrient content of the soil, the location of the available field, the equipment and manure management system utilized (e.g. liquid or solid), the farm-specific regulatory guidelines for manure management, as well as the facilities and manure storage capacity of the operation. In order to account for the value of the nutrients within the manure as a source of crop nutrients, the value of the nutrients within the manure (VN) must be subtracted from the cost of manure disposal; thus reflecting the net costs of the manure. Collectively, this allows for manure disposal costs to be generally expressed as:

$$(10)\, MDC = f(TM, P_e, N_e, Z) - VN \,.$$

It is important to note that the total quantity and nutrient density of the manure is directly affected by the nutrient content of the diet, the number of animals, and the number of days on feed. This is where the amount of DGS included in the diet affects manure disposal costs. Given that DGS are high in both protein and phosphorus and its inclusion into the diet impacts ADG and thus DOF, DGS inclusion directly affects both the quantity and nutrient density of the manure excreted.

(4.2.5) Fixed Costs

The impacts of incorporating DGS into finishing cattle diets on operational fixed costs are not explored within the context of this thesis. It is assumed that these costs are unaffected in the short run by a producer's decision to include DGS, and that the operation has the physical capacity/facilities for any DGS inclusion level considered. However, it is important to note that for some operations, fixed costs, such as adequate storage facilities, may be affected in the long run.

Due to the fact that fixed costs and many costs typically considered variable costs are not included; any cited profit throughout the remainder of this thesis will appear high. Nevertheless, total profit is not of principle concern, but rather how DGS inclusion rates affect changes in profit.

CHAPTER 5: ESTABLISHING THE BASE MODEL - METHODS AND DATA

As mentioned in chapter two, one common approach to economic ration formulation modeling is through the use of linear programming. However, due to the non-linearity of the problem presented above, a non-linear mathematical optimization model was developed, which directly incorporates the relationships defined in chapter four. This chapter will describe the direct implementation of the conceptual framework, along with the base case parameter assumptions, which are listed within table 4 in the order they are discussed.

Prior to discussion specifically related to the implementation of the various components of profit (equation 1), the animal response functions identified within these components will first be presented. The following section will provide an explanation regarding how the average daily gain (ADG) and dry matter intake (DMI) equations defined generally in equations (5) and (7) were derived. Then, subsequent sections will discuss the implementation of the profit equation component by component.

(5.1) Animal Response Function Estimation

Rather than adopting an ADG and DMI equation from a single feeding trial, these equations were estimated using data from multiple feeding trials. This was deemed particularly important due to the fact that the meta-analysis data from the feeding trials collected by Dr. Steven Rust (table 2), presented and discussed within chapter two, illustrated significant variation across trials regarding the degree and significance to which the inclusion level of distiller's grains impacts animal response (e.g. ADG, DMI, and marbling).

After diagnostic analysis of the meta-analysis data, which revealed significant leverage within individual trials, all observations where the inclusion of distiller's grains with solubles (DGS) was greater than 50% were eliminated. After initial data cleaning, seemingly unrelated regression (SUR) techniques were used to jointly estimate ADG and DMI. Using a systems approach to estimate ADG and DMI is a rather novel concept, which has rarely, if ever, been previously applied. However, unobservable (or non-recorded) factors which may vary within a trial are likely to influence both ADG and DMI, and SUR procedures take this correlation in the error terms across the system of equations into account (Wooldridge 2002). Furthermore, theoretically consistent recovery of feed to gain estimates (via. adding up restrictions) are easily obtainable from a system of estimated equations. For these reasons, SUR regression techniques were deemed more appropriate than single equation methods.

Regression results are shown in equations (11) and (12) below, where X_{DDGS} is the percent dried distiller's grains with solubles (DDGS) in the diet and X_{WDGS} is the percent wet distiller's grains with solubles (WDGS) in the ration. P-values are reported in parentheses below each equation. A quadratic relationship was found between DDGS inclusion and both ADG and DMI, as well as between WDGS inclusion and both response functions. How ADG and DMI are affected by DDGS and WDGS inclusion levels are illustrated within figures F and G, respectively. Before settling on these quadratic relationships, linear specifications were first considered. A strong quadratic relationship was evident between X_{WDGS} and both ADG and DMI, while the quadratic term for DDGS inclusion was not found to be as statistically significant. Nonetheless, quadratic equations were deemed appropriate for both DGS models[6].

$$(11)\ ADG = 3.6206 + 0.0160 * X_{DDGS} - 0.0003 * X^2_{DDGS} + 0.0244 * X_{WDGS} - 0.0005 * X^2_{WDGS}$$

R^2=0.9604 (0.0100) (0.0120) (0.0000) (0.0000)

(12)

$$DMI = 22.8655 + 0.0559 * X_{DDGS} - 0.0011 * X^2_{DDGS} + 0.0574 * X_{WDGS} - 0.0020 * X^2_{WDGS}$$

R^2=0.9629 (0.0140) (0.0540) (0.0080) (0.0000)

Regressions also incorporated trial dummy variables (not shown) in order to account for any differences across trials. Given that no a priori reason suggests selecting a particular trial dummy variable to represent the intercept term over another, trial dummy coefficients were averaged to obtain estimated ADG and DMI intercepts. This is why there are no p-values shown for the presented constants. Additionally, both WDGS and DDGS were included within the same equation. However, it is important to note that this does not mean that both WDGS and DDGS were included within the same treatment, or that anything can be inferred regarding how an animal can be predicted to respond to a ration containing both DGS types. Such inferences cannot be made, as affects of mixed rations were not observed within any of the feeding trials used to estimate these equations.

Figure H plots the relationship between DGS inclusion level and feed to gain (DMI / ADG) derived from equations (11) and (12). As illustrated, these equations suggest that, relative to corn, WDGS inclusion has a negative impact on feed to gain (increased feed efficiency), while DDGS inclusion has relatively little impact on feed to

[6] However, re-estimation of these animal response functions is encouraged as new data becomes available.

gain. These equations illustrate relationships which are consistent with the trial plots presented within chapter two (figures B1 and B2), where increasing WDGS was found to have a negative impact on feed to gain and DDGS was found to have little to no affect.

The derived relationships between DGS inclusion and feed to gain presented in figure H are also compared with the feed to gain equations estimated directly from the data-set using standard ordinary least squares (OLS) estimation procedures (equation 13, p-values are reported within parentheses). As one can observe, these two methods produce similar results; however, the OLS approach produced F/G estimates that were unambiguously higher (less feed efficient) than those derived from the SUR estimates of ADG and DMI. It can also be noted that when using OLS to estimate F/G directly from the data, DDGS inclusion was not found to have a statistically significant affect on feed to gain, and only a linear relationship between WDGS and feed to gain was significant.

$$(13)\ F/G = 6.3610 - \underset{(0.152)}{0.0131X_{DDGS}} + \underset{(0.195)}{0.0003X_{DDGS}^2} - \underset{(0.019)}{0.0206X_{WDGS}} + \underset{(0.478)}{0.0001X_{WDGS}^2}$$

Additionally, OLS estimation procedures were used to derive a function for marbling. However, the inclusion level of DGS within the diet was not found to have a statistically significant impact on marbling score. Therefore, this equation was dropped from the model. Given that limited data was available to evaluate the impact of DGS inclusion on carcass quality, re-examination of such regressions is needed as additional feeding trials observing such data are conducted.

(5.2) Revenue (R)

As described within the conceptual framework, revenue can be defined as the price of the output (P_y) times the finished weight (Y), where the price of the output is a function of quality (g(Q)). Furthermore, quality was considered to be a function of DGS inclusion (f(X_{DGS}). Therefore, revenue became defined as: $R = P_y Y = g(f(X_{DGS})) * Y$.

The average finished weight from the meta-analysis data-set (1,250 lbs) was used as the target weight (Y). However, given that when marbling scores were regressed against DGS inclusion, DGS inclusion was deemed to be statistically insignificant, the equation where output is a function of quality was dropped from the model. As a result, a flat $100 per hundred weight was used as the finished weight price; with no discount or premium for the level of quality. Given that information on growth rates and daily intake for individual growth stages was unavailable, Y was held constant, preventing this variable from becoming a choice variable as conceptual theory would suggest. However, the DGS concentration still affects the number of days required to reach this targeted finish weight of 1,250 lbs through its effect on daily gain. Therefore, while total revenue equaled $1,250 per finished animal, regardless of the amount of distiller's grains included within the ration, total costs are affected by alternative DGS concentrations.

(5.3) Feed Costs

Equation (6) within the conceptual framework defined feed costs as:

$FC = [\sum_{i=1}^{n}(X_i V_i)] * DMI * DOF]$, where X_i was the percent of feed ingredient 'i' in the ration, V_i was the cost of feed 'i', and DOF was the number of days on feed. Recall that the cost of the feed (V_i) included not only the price of the feed but also any additional transport, handling, or storage costs associated with that feed.

All base case feed ingredient prices are listed in table 4. The listed corn price of \$2.78/bu was the average price for corn based out of Chicago, IL reported on a weekly basis by the Livestock Marketing Information Center (LMIC) during the February 2006 to March 2007 time period. Then, the corn price data set (\$/bu) and the DGS price data (\$/ton), also reported on a weekly basis by the LMIC for DGS based out of Springfield, IL for the time period of February 2006 to March 2007, were converted to \$/lb DM. This time period was chosen as this is the time period over which DGS price data has been reported. After converting both the corn and DGS price series to \$/lb DM, the base case prices for DDGS and WDGS were calculated using the average DGS (\$/lb DM) to corn price (\$/lb DM) ratios. The average DDGS/corn price ratio was 1.0 and the average WDGS to corn price ratio was 0.92. This made the "at the plant" price of DDGS \$101.53/ton and the price of WDGS \$31.14/ton within the base case model. The price of corn silage was estimated ($\hat{P}_{cs}$) using the following formula: $\hat{P}_{cs} = 7 + 7 * P_{corn}$, where P_{corn} is the price of corn (Black 2007). Hay and Soybean meal were priced using their monthly average prices as reported within the Feed Grains Database (January 06-March 07; ERS). Limestone was priced by personal communication with experts familiar with the industry. Urea was priced at its weekly average (February 2006- March 2007), as reported out of Minneapolis, MN by *Feedstuffs* magazine.

Initially, DGS transportation distance (from the plant to the feed bunk) was set at zero. However, as this distance was increased in subsequent sensitivity analyzes, a quoted cost of \$2.50 per loaded mile (1 load = 25 tons) was incorporated (Vander Pol, et al. 2006b). Although, some may argue that feeding DGS, WDGS in particular, increases handling and storage costs, these costs were initially assumed to be zero.

Nutrient and Feed Ingredient Constraints

In addition to the feed costs, certain nutritional and feed ingredient constraints were imposed within the model. The nutritional constraints imposed in the model, as identified throughout the literature and reviewed by beef nutrition specialist, Dr. Steven Rust, are listed in table 4. Due to the discrepancies throughout the literature regarding the quality of protein within DGS and whether or not the quality differs between WDGS and DDGS, a minimum urea constraint was set at 0.30% as a safeguard[7]. Other feed ingredient constraints presented within table 4 were designed to keep these ingredients within a typical range. Due to the fact that a complete biological system is not modeled, there are reasons for keeping these ingredients within these ranges that are not captured by nutrient constraints or the response functions.

Nutrient composition values for all feed ingredients except for DGS were as reported by the National Research Council (NRC) *Nutrient Requirements of Beef Cattle* publication (1996). Given that research has indicated that the nutrient composition of DGS has changed since the NRC reported values were collected, average values from the 34 U.S. ethanol plants collected by the University of Minnesota were used (2006). Nutritional composition values for all feed ingredients are listed within table 5.

[7] This constraint will be evaluated within subsequent sensitivity analysis.

(5.4) Other Variable Costs

The other variable costs (VC) component of profit (equation 1), presented within the conceptual framework, included yardage costs (YC) and daily interest charges. This component of the model was expressed as $VC = [YC + i * (C_{fs} + 0.5 * FC)] * DOF$, where i is the daily interest rate, C_{fs} is the purchase cost of the feeder steer and remaining variables are as previously defined. Within the base case model, 8% was the assumed yearly interest rate and \$0.33/day was the assumed yardage cost. As for the cost of the feeder steer, this cost was calculated by taking the average starting weight within the meta-analysis dataset[8] (775lbs) and multiplying it by the reported price of a feeder steer based out of Springfield, IL on May 11, 2007 (\$93.49/cwt; AMS).

(5.5) Manure Disposal Costs

The main approach used to determine the manure disposal costs (MDC) in this model follows that presented by Hadrich (2007), while the excretion functions employed are those found within the American Society of Agricultural Engineer's publication on "Manure Production and Characteristics" (2005). Hadrich (2007), Harrigan (2001), and the *Manure Distribution Cost Analyzer* developed by Dr. Raymond Massey of the University of Missouri (1998) calculate manure disposal costs based on the amount of time required to load, haul, unload, and incorporate the manure onto available crop acres. Using this approach the cost of manure disposal per head (h) becomes:

(14) $MDC = [DC * (LT + TT + UT + IT)] / h$,

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[8] After observations where DGS inclusion levels less than 50% were eliminated.

where DC is the hourly cost incurred, LT is total loading time, TT is total transportation time, UT is total unloading time, and IT is total incorporation time. [9]

This section will now go through an explanation of how each of these components were calculated and the base case assumptions that were assumed. To start off, a liquid manure system was assumed and the hourly disposal cost (DC) was adapted directly from Hadrich (2007) as being \$150/hr. This hourly cost includes yearly machinery and labor costs for loading, transporting, unloading, and incorporating the manure (Harrigan 2001). The remaining components are not as straightforward and will now be examined in turn.[10]

(5.5.1) Loading Time

Total loading time equals the amount of time required to load the manure (lt) multiplied by the number of loads (L) needed to dispose of total farm manure. The number of loads needed depends on the total amount of manure produced by the operation (TM), the amount of manure that can be applied to a particular field (AG_{mcr}), and the tank size (ts). As was adopted from Hadrich (2007), the tank size was assumed to be 6,000 gallons and loading time (lt) was assumed to be 12.11[11] minutes per load. The number of loads required to dispose of the manure was calculated as follows:

$$(15)\, L = \sum_{m}^{T}\sum_{c}^{N}\sum_{r}^{3} AG_{mcr} / ts,$$

[9] However, it is important to note that many states place additional requirements on operations of 1,000 animal units or more (1,000 lb steer = 1 au). Such implications are not explored within the scope of this thesis.

[10] Quoted times required for given tasks throughout the remainder of this section are often a function of the equipment used; assumptions regarding equipment type are discussed by Hadrich (2007).

[11] The 12.11 minutes per load is a function of the pump, agitator and spreader used (Hadrich 2007).

where; $m=1,2,\ldots.T$, $c=1,2,\ldots N$, and $r=1,2,3$ (or until all manure is disposed); AG_{mcr} is the allowable gallons of manure that can be applied to a particular field of crop 'c', which falls under application rate 'r', and is located at mileage distance category 'm'. While $m=1,2,\ldots.T$, $c=1,2,\ldots,N$ and $r=1,2,3$, TM will determine when these loops will be terminated. For instance, the 'm' loop may never reach T because all manure may be disposed of by the time the 4th mileage category is reached. The model is designed to dispose of the manure in the fields closest to the feedlot first and then travel further out as necessary to dispose of TM.

The hypothetical scenario established within the base case model assumes that there are three crop types accessible for manure disposal (meaning the feedlot operator either owns the land or has access rights to the land): corn, corn silage, and soybeans. The model also assumes that there are 16 mileage categories, one every mile until 10 miles is reached, after which point there is one every five miles until 40 miles is reached. The model considers such a large range of mileages to ensure that all manure can be disposed of, even in cases where larger operations (>1,000 head) are considered.

The amount of manure that can be applied to a particular field (AG_{mcr}) depends not only on the acreage of that field, but also on the agronomic nutrient removal rates of the crop grown on those acres and the regulatory guidelines for manure application. State guidelines dictate the amount of manure that can be applied under given soil nutrient levels. According to the Michigan Right to Farm guidelines, manure can be applied at the nitrogen removal rate (r=1) if the soils contain less than 150 lbs of phosphorus (P) per acre, the phosphorus removal rate (r=2) if the soil contains between 150 and 300 lbs of

P/ac, and that it may not be applied (r=3) if the soils exceed 300 lbs of P/ac (Michigan Department of Agriculture 2006). AG_{mcr} can now be expressed as:

(16) $AG_{mcr} = (RR_{cr} / D_r) * AC_{mcr}]$,

where RR_{cr} is the nutrient removal rate (lbs/acre) for crop 'c' within application rate category 'r', D_r is the manure density rate used for calculating allowable manure application per acre, and AC_{mcr} is the acres of crop 'c' within application rate 'r' at mileage distance category 'm'. Crop removal rates (lbs/unit of yield) identified by Warncke, et al. (2004) are used along with potential yield information, to calculate RR_{cr} (lbs/acre), presented within table 6. Notice that nitrogen credits, which are based on nitrogen fixation in legume crops (Hadrich 2007), are subtracted from the nitrogen removal rate of soybeans.

The next step was to calculate the nutrient density of the manure (D_r). Total nitrogen excreted (N_e) divided by total manure volume (TM) was used to calculate nitrogen density (D_1) (equation 17). P_2O_5 density (D_2) was calculated by taking total phosphorus excreted (P_e) multiplied by 2.3 (conversion between phosphorus and P_2O_5) and dividing by TM (equation 18). D_3 was set at 1; although, the value D_3 was irrelevant since AG_{mcr} equals zero when r =3.

(17) $D_1 = N_e / TM$

(18) $D_2 = (P_e * 2.3) / TM$

The following equations, as presented within the American Society of Agricultural Engineer's publication on "Manure Production and Characteristics" (2005), define how N_e, P_e and TM were calculated:

$$(19)\ N_e = ([DMI * C_{cp} * DOF * (1/6.25)] - [41.2 * (Y - SW)]$$

$$+ \{0.243 * DOF * [(Y + SW)/2]^{0.75} * [SRW/(Y * 0.96)]^{0.75} * [(Y - SW)/DOF]^{1.097}\}) * h,$$

$$(20)\ P_e = [(DMI * C_p * DOF) - [10 * (Y - SW)] + \{0.0592 * DOF * [(Y + SW)/2]^{0.75}$$

$$* [SRW/(Y * 0.96)]^{0.75} * [(Y - SW)/DOF]^{1.097}\}] * h, \text{ and}$$

$$(21)\ TM = \{[DMI * (1 - DMD/100)] + 20.3 * [0.06 * (Y + SW)/2]/S\} * h,$$

where dietary concentration of crude protein (C_{cp}) and phosphorus (C_p) are defined within equations (22) and (23), SW is the starting weight of the animal (775lbs), SRW is the standard reference weight for expected final body fat for Choice (478kg) (ASAE 2005), DMD is the dry matter digestibility of the ration (80%) (ASAE 2005), and S is the percent solids excreted (8%) (ASAE 2005), and all other variables are as previously defined.

$$(22)\ C_{cp} = \sum_{i}^{n} X_i * CP_i ,$$

$$(23)\ C_p = \sum_{i}^{n} X_i * P_i ,$$

where X_i is the percent DM of feed ingredient 'i' in the diet, CP_i is the percent crude protein in feed ingredient 'i', and P_i is the percent phosphorus in feed ingredient 'i'.

First, all weights within the model were converted to their appropriate units as specified within the ASAE publication (2005). Then, estimates from each of these excretion functions were converted to pounds. Tables 7a and 7b present estimated nutrient excretion levels using the above formulations at various DDGS and WDGS inclusion levels, respectively. These estimates were calculated by forcing the optimization model to include a given DGS inclusion level. The model then calculated estimated DMI and DOF using equations (11), (12), and (4b) to find the profit maximizing ration given a particular DGS inclusion rate. Then, nutrient excretion levels were calculated according to equations (19) and (20) using all previously defined weight parameters (i.e. $SW = 775$ lbs and $Y = 1{,}250$ lbs).

Recall from equation (16), that once the allowable application rate for a particular crop acre (RR_{cr} / D_r) is calculated, it is then multiplied by the total acreage of that crop to find the allowable gallons of manure that can be applied to a particular field (AG_{mcr}). The amount of crop ' c ' acres within application rate ' r ' at mileage distance category ' m ' (AC_{mcr}) to which the producer has access established within the base case model was purely hypothetical. Nevertheless, parameters were established after talking with various feedlot operators in order to obtain realistic estimates. Within our base case farm, 500 acres of land were assumed accessible every mile, where 45% of these acres are corn, 45% soybean, and 10% corn silage acres. Within this hypothetical model, 40% of the acres are available for manure application at the nitrogen removal rate, 40% are available for manure application at the phosphorus removal rate, and 20% exceed soil phosphorus limits and are unavailable for manure disposal. For instance, of the 500 acres available within the 1st mile of the base case model; 225 are corn acres, of which 90 acres can have manure applied at the nitrogen removal rate, 90 acres can have manure applied at the phosphorus removal rate, and 45 are not available for manure application.

(5.5.2) Transportation Time

Total transportation time (TT) depends not only on the speed and distance traveled but also on the number of loads, calculated within the "loading time" section above. TT is defined as:

$$(24)\ TT = \sum_{m}^{T} \sum_{c}^{N} \sum_{r}^{3} L_{mcr} * M_m * (ST + SR),$$

where; $m = 1,2,\ldots.T$, $c = 1,2,\ldots N$, and $r = 1,2,3$ (or until all manure is disposed); L_{mcr} equals the number of loads going to crop ' c ', application rate ' r ', at mileage distance ' m '; M_m is the number of miles within mileage distance category 'm'; ST is the hours required to travel one mile (1/mph) while traveling to the field; and SR is the hours required per mile returning from the field. Travel speeds to and from the field were assumed to be 14 and 17 miles per hour, respectively (Harrigan 2001)[12].

(5.5.3) Unloading Time

Unloading time is calculated by taking the amount of time required to unload one tank multiplied by the number of loads (L). The time required to unload one tank depends on the time required to cover 1 acre (b) multiplied by the number of acres covered per tank, where b was assumed to be 6.19 minutes per acre (Hadrich 2007). In order to calculate the number of acres covered per tank, the tank size (ts) is divided by the allowable gallons of manure that can be applied.

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[12] Travel speeds will be a function of spreader (e.g. tractor-drawn tank, truck mounted, nurse trucks), road conditions, distance and whether the spreader is empty or full (Harrigan 2001).

As per these definitions, total unloading time (UT) was calculated as follows:

$$(25)\ UT = \sum_{m}^{T}\sum_{c}^{N}\sum_{r}^{3}(ts / AG_{mcr}) * b * L_{mcr}\ .$$

<u>(5.5.4) Incorporation Time</u>

Total incorporation time (IT) was calculated by taking the time required to incorporate one acre (assumed to be 2.75 minutes/acre) multiplied by the number of acres on which manure was actually applied (Hadrich 2007). Note, this is not strictly AC_{mcr}, as the model does not necessarily utilize all accessible acreage, only the acres required to dispose of total farm manure at the lowest feasible cost.

CHAPTER 6: RESULTS AND SENSITIVITY ANALYSIS

(6.1) Base Model Results

Model results for optimal dried distiller's grains with solubles (DDGS) and wet distiller's grains with solubles (WDGS) inclusion rates under the base case assumptions listed within table 4 are presented within tables 8a and 8b, respectively. The optimal DDGS inclusion level under these base case assumptions and prices is 18.4%, while the optimal WDGS inclusion level is 29.7%. Base model results indicate that incorporating distiller's grains with solubles (DGS) into beef feedlot rations at typically cited maximum DGS inclusion levels, in a range of 30% to 40% (Benson, et al. 2005; Buckner, et al. 2007a; Tjardes and Wright 2002; Lardy 2003; Vander Pol, et al. 2006a), may not always be the most economical. For instance, model results indicate that over inclusion may still result even when compared with the Vander Pol, et al. (2006b) WDGS study. Vander Pol, et al (2006b) also incorporated several economical factors and biological response functions, and concluded that 40% was an economical WDGS inclusion rate for a feedlot located up to 100 miles from an ethanol facility.

Nevertheless, it is imprudent to say that economical inclusion rates couldn't reach these levels under alternative scenarios and assumptions. For these reasons, the remainder of this chapter will evaluate how economically optimal inclusion levels of DGS into beef feedlot rations are affected by other possible scenarios. Is the range of 30% to 40% inclusion an economical DGS inclusion level in certain scenarios? With what frequency is feeding within this range optimal? How do model assumptions regarding manure disposal costs impact optimal DGS inclusion rates? These are just a few of the many questions to be explored within this chapter.

The base model shadow values are reported within table 9. Traditionally, a shadow value is the amount by which the objective function could be improved if that constraint were to be relaxed by one unit. Any shadow value greater than zero indicates a binding constraint. However, it is important to note that due to the non-linearity of this model, caution is advised when interpreting these shadow values according to the traditional definition. Therefore, all subsequently reported shadow values were only used for the purposes of identifying the binding constraints, sensitivity analyzes on the identified constraints were then conducted to evaluate the impact of alternative constraint values on optimized profits and DGS inclusion levels. These sensitivity analyzes on binding nutrient and feed ingredient constraints are ensued in section 6.2.1.

Additionally, it is noted that common measures were undertaken to increase the probability that model results are at the global optimum. First, starting value sensitivity analysis was conducted across many of the subsequently examined model scenarios. Results indicated that the optimization model was in fact insensitive to chosen starting values. Next, second order conditions were evaluated. Since Matlab optimizes by minimizing the defined objective function (e.g. negative profit), the Hessian matrix must be positive definite in order for second order conditions to be met. A sufficient condition for positive definite matrices is that all determinants be positive. Therefore, each determinant of resulting Hessian matrices were evaluated, and across all evaluated model scenarios, results indicated that second order conditions were in fact met.

(6.2) Sensitivity Analysis

While the base case results present economically optimal DGS inclusion rates calculated under a set of base assumptions, it is important to keep in mind that many of these assumptions will not hold in all situations. Given, the uncertain nature of the ethanol and the distiller's grains markets, established base model DGS and corn prices may not necessarily represent future price relationships. This uncertainty, coupled with the fact that no two feedlots face identical cost parameters, highlights the need for thorough sensitivity analysis. While this section does not attempt to cover an exhaustive list of plausible scenarios, it is intended to explore the implications of key parameter assumptions underlying the base case model on optimal DGS inclusion rates.

Model sensitivity to parameter assumptions made within the feed cost, other variable cost, and manure disposal cost components of the profit function (outlined within chapter four) will now be analyzed in turn. Additionally, model sensitivity to binding nutrient and feed ingredient constraints will be included in the discussion regarding model sensitivity to alternative feed cost parameters. This will be followed by a discussion regarding the uncertainty in the animal response function estimations, and how risk arising from this uncertainty may impact optimal DGS inclusion levels.

<u>(6.2.1) Alternative Feed Cost Parameters</u>

The base case model presented optimal DGS inclusion levels given a particular set of feed ingredient prices and was subject to a set of nutrient and feed ingredient constraints (shown within table 4). This section will examine how alternative price scenarios affect optimal DGS inclusion rates. Additionally, model sensitivity to established nutrient and feed ingredient constraints specified within the base model will be examined under these alternative price scenarios.

Not only are market prices continually changing, but the transportation and additional handling and/or storage costs associated with feeding DGS vary from operation to operation and across time. Therefore, a wide range of price relationships must be examined. Rather than attempting to show model results under the vast array of possible transport, feed price, and handling/storage cost scenarios, this section will evaluate optimal DGS inclusion levels under a wide range of various DGS to corn real price relationships. Here the "real price ratio" accounts for not only purchase prices, but also any additional transportation, handling and/or storage costs relevant to the producer. Limiting the analysis to the range of historical DGS/corn feed price ratios would only be considered a reasonable range of price scenarios for a producer located next to an ethanol facility and who does not incur any additional handling and or storage costs when incorporating DGS into their feedlot rations. By extending this range of examined price scenarios, a producer who does incur these additional costs will be able to utilize model results, utilizing the real DGS/corn price ratio relevant to their individual operation.

Furthermore, since WDGS are generally preferred over DDGS (as they have been found to be the more feed efficient type of DGS), various WDGS/DDGS real price relationships will be examined in order to evaluate the real WDGS/DDGS price ratio at which it becomes economically optimal to switch from WDGS to DDGS. Again, by accounting for the real prices of each feed, additional transport and/or handling and storage costs that may be incurred from feeding WDGS over DDGS will be automatically included within the analysis of this trade-off. By viewing the price relationships as real prices, as opposed to at-the-plant purchase prices, fewer scenarios will need to be examined. Again, this will allow a producer, facing its own unique costs, to utilize results by determining the real price ratio between WDGS and DDGS facing their individual operation.

DGS/Corn Price Relationships

The base case DGS/corn price ratios shown within table 4 were established using historical DGS/corn feed price ratio averages obtained from the Livestock Marketing Information Center (LMIC), as reported for corn and DGS based out of Illinois between February 2006 and March 2007. The average DDGS/corn feed price ratio was 1.0 and the average WDGS/corn feed price ratio was 0.92 (compared on a $/lb DM basis). However, due to price volatility experienced within the DGS and corn markets, sensitivity analyzes to these price assumptions were conducted. As an evaluation of this sensitivity, figures I1 and I2 present optimal DDGS and WDGS inclusion levels, respectively, under a wide range of DGS/corn real price relationships. Additionally, a range of corn price scenarios are examined: $2.00/bu, $2.78/bu, and $4.18/bu; where $2.00/bu corn was the minimum corn price reported by the LMIC, $2.78/bu was the average, and $4.18/bu was the maximum.

Over the historical DDGS/corn feed price ratio range of 0.78 to 1.24, the optimal DDGS inclusion rate ranged from 29.7% to 8.2% (figure I1). In contrast, optimal WDGS inclusion remained at a constant 29.7% over its historical WDGS/corn price range of 0.74

to 1.01 (figure I2). The hash marks found within figures I1 and I2 (and in subsequent figures) illustrate these historical DGS/corn feed price ratio ranges.

As the base corn price of $2.78/bu was increased ($4.18/bu) or decreased ($2.00/bu), optimal DGS inclusion levels did not change significantly over the range of historical DGS/corn feed price ratios. However, there reached a reduced WDGS/corn real price ratio where the optimal WDGS inclusion increased to about 37.8% when the corn price was increased from $2.78/bu to $4.18/bu. Due to the fact that the fat constraint was previously binding within the base WDGS model (table 9), increased levels of hay and soybean meal were incorporated at these low WDGS/corn price ratios with a high base corn price to allow the maximum WDGS inclusion level to reach this 37.8%. This occurs because both hay and soybean meal have lower levels of fat content than DGS, corn, and corn silage. Due to the relatively high prices listed for soybean meal and hay, it was not previously optimal to include these feeds in the ration. However, now that DGS are significantly less expensive relative to corn, the economic incentive to increase the DGS inclusion level begins to outweigh the additional cost of soybean meal and hay.

Another observation to clarify regarding figures I1 and I2 is that after a certain increased DGS/corn real price ratio, there is a reversal in the order of the data series. When the price ratio is low, increasing the corn price increases the cost differential between DGS and corn to the advantage of DGS; therefore, the optimal inclusion of DGS increases. Conversely, when the DGS/corn real price ratio is high, increasing the corn price increases the cost differential between DGS and corn, but to the advantage of corn; thereby causing the optimal DGS inclusion level to decline. This switch occurs at 1.0 in the DDGS model; whereas, in the WDGS model this point occurs at 1.2. The differences in these two points can be attributed to the greater feed efficiency realized from WDGS inclusion.

As mentioned previously, the range of price ratios shown within figures I1 and I2 were extended beyond their historical DGS/corn feed price ratios in order to account for any additional transport and storage/handling costs that may be incurred in addition to the direct feed costs. The following is an example of how these figures may be used to find optimal WDGS inclusion levels for two hypothetical producers facing different transportation costs.

Producer A is located directly next to an ethanol plant which is charging \$31.14/ton for WDGS (\$0.052/lb DM) and faces a WDGS/corn price ratio of 0.92 (corn price = \$2.78/bu as fed or \$0.056/lb DM), making the optimal WDGS inclusion for this producer 29.7% (table 8b). Producer B is located 100 miles from the ethanol plant, but is quoted the same at-the-plant WDGS purchase price of \$31.14/ton and the same real corn price of \$2.78/bu. At a quoted transport cost of \$2.50 per loaded mile (Vander Pol, et al. 2006b), and assuming that the full load of 25 tons is utilized, every 50 miles of transport increases the cost of DGS by \$5/ton. At \$5/ton, the cost of WDGS (30% DM) increases by \$0.008/lb DM and the cost of DDGS (90% DM) by \$0.003/lb DM every 50 miles. This means that producer B has to add \$0.016/lb DM to the price of the feed, making the real price of WDGS \$0.068/lb DM. Thus, the WDGS/corn real price ratio facing producer B is approximately 1.21, making optimal WDGS inclusion about 21.8% (figure I2).

Figures J1 and J2 illustrate how increasing transport distance affects optimal DDGS and WDGS inclusion levels differently, holding all other base case assumptions constant. Note that this analysis assumes the corn price of $2.78/bu includes transportation expenses. Also notice that the range of DGS/corn price relationships have been constricted from those shown in figures I1 and I2, as transport costs are now being directly incorporated. As expected, increasing the transport distance has a much greater impact on optimal WDGS inclusion rates than on optimal DDGS inclusion. At the average WDGS/corn price ratio (0.92) and average corn price ($2.78/bu), about 22% to 30% can be economically fed up to 100 miles, between 15% and 22% for the next 50 miles (100-150 miles), and 8% to 15% at transport distances between 150 to 200 miles. This range in optimal WDGS inclusion levels as transport distance increases from 0 to 200 miles is much broader than that for optimal DDGS inclusion levels. At the average DDGS/corn price ratio (1.00) and an average corn price ($2.78/bu), about 13% to 18% can be economically fed up to 100 miles, and between 8% and 13% for the next 100 miles.

Nutrient and Feed Constraints

Recall that the fat was a binding nutritional constraint within the base WDGS model (table 9). The shadow value for fat was 350.5 within the WDGS model. Recall that the nutritional constraints specified that fat intake be less than 6.0% of ration dry matter. Therefore, traditional definitions of "shadow value" would interpret this value of 350.5 to imply that the profit maximizing ration could be re-distributed allowing total profit to increase by $3.51 per finished animal if this constraint could be relaxed (increased) by 1%. To gain perspective, this would increase profits for the 1,000 head operation by $3,510.

However, as noted previously, caution is advised when interpreting these shadow-values according to the traditional definition due to the non-linearity of this model. Rather than interpreting the shadow values directly, reported shadow values are used to identify binding constraints. Then, subsequent sensitivity analyzes were conducted on these identified constraints to directly evaluate model sensitivity to alternative constraint values. Tables 10a (DDGS model) and 10b (WDGS model) present ration formulation results and shadow values across the wide range of examined DGS/corn real price ratios. Notice that the fat constraint is only binding when DGS are priced relatively low or when DGS inclusion is greater than 22%. Additionally, the maximum roughage and maximum limestone constraint are binding at all price scenarios, where the minimum urea constraint is binding only when DGS inclusion levels are greater than 7%. These feed ingredient constraints may be binding due in part to the fact that a fully developed nutritional system is not captured, meaning common reasons for not including exorbitantly high levels of these ingredients are not included within the model; hence why these constraints were imposed to begin with. Nevertheless, model sensitivity will be conducted on these constraints. Additionally, it may be noted that the economic incentive for adjusting these constraints may not necessarily justify ration alterations.

Model sensitivity was first conducted on the fat constraint, then as subsequent need arose, on the crude protein and sulfur constraints. Afterward, sensitivity analyzes to changes in the binding feed ingredient constraints were conducted. Sensitivity results are shown for the DDGS and WDGS models are presented within tables 11a and 11b, respectively. For each of the sensitivity analyzes, the base case constraint was both increased and decreased by 25% and evaluated at the historically maximum DGS/corn feed price ratio, the average price ratio, and the minimum price ratio.

Sensitivity analysis was first conducted on the fat constraint. Due to the fact that the fat constraint was not binding within the base case DDGS model (table 9), relaxing (increasing) the fat constraint from 6% to 7.5% did not significantly impact optimal DDGS inclusion levels. In comparison, relaxing the fat constraint by 25% increased the optimal WDGS inclusion level by as much as 11% (min WDGS/corn feed price ratio). On the other hand, reducing the amount of fat allowed within the diet by 25% decreased optimal DGS inclusion within both models to 6.9%, under all three price scenarios, and decreased profits by as much as \$19.41/head (min WDGS/corn feed price ratio). Nevertheless, this sensitivity analysis revealed an economic profit incentive to allow increased levels of fat within the diet. By relaxing the fat constraint from 6% to 7.5%, profit increased by \$0.26/head within the WDGS model, under the average WDGS/corn feed price ratio, and as the DGS/corn price ratio decreased this economic incentive increased. While the overall profit incentive to increase the fat content of the diet exists due to the increase of \$0.26 per finished animal, this is subjective to the size of the operation, such minimal increases may not necessarily warrant ration alterations in all scenarios.

When the fat constraint was decreased to 4.5% of ration dry matter, the crude protein constraint becomes binding. Therefore, holding the fat constraint at its restricted level of 4.5%, sensitivity analysis was then conducted on the crude protein constraint. The results from this sensitivity analysis can also be found within tables 11A and 11B. As expected, due to the high protein content of DGS, optimal inclusion rates increased under the tightened (increased) crude protein requirement and decreased when this requirement was relaxed (decreased).

The final sensitivity analysis conducted on the nutritional constraints, was on the sulfur constraint (also shown within tables 11A and 11B). This analysis may be particularly important given the consequences of exceeding the sulfur constraint, which can lead to poliocenphalomalacia, a highly fatal disease. Feedlot operators located in areas where there is increased dietary sulfur intake coming from the animal's drinking water may want to be especially cautious. Operators concerned about their animal's sulfur intake may want to tighten (decrease) the sulfur constraint to ensure that total intake does not exceed 0.40%. For this reason, sensitivity analysis was first conducted for a 25% decrease in the sulfur limit, again holding all other base assumptions constant. However, results indicated that DGS inclusion did not reach a level to where this constraint became binding. Nevertheless, given the potential severity of disregarding the sensitivity analysis of this constraint, an additional analysis was conducted where a relaxed (increased) fat constraint of 7.5% was implemented along with the tighter (decreased) sulfur constraint. This scenario was chosen given the profit incentive for increasing the fat constraint and allowing for higher DGS inclusion rates. In this case the sulfur constraint became highly binding within the WDGS model, limiting the maximum economically optimal inclusion rate to 30.5% under all three examined price scenarios, reduced from 40.9% (scenario where solely the fat constraint was relaxed).

After performing sensitivity analysis on all of the nutritional constraints that were found to be binding within the base model, sensitivity analysis was then conducted on the feed ingredient constraints that were binding under the base case assumptions (maximum roughage, minimum urea, and maximum limestone; table 9). As in the nutrient constraint analyzes, each of these constraints were both increased and decreased by 25% and optimal profit and DGS inclusion results were evaluated.

While relaxing (increasing) the maximum roughage constraint altered optimal DGS inclusion rates by less than 1%, it did slightly increase profits within both models (tables 11A and 11B). Due to the price of corn silage, \$26.46/ton, increasing this constraint allowed corn silage to replace corn, not DGS. Therefore, the price of corn silage underlies the magnitude of the profit incentive for increasing dietary roughage concentration levels, not increasing/decreasing DGS inclusion rates.

Then, given the fact that the binding minimum urea constraint was established as a safety measure to ensure all protein requirements were met, and the fact that some researchers would argue that this measure may be unnecessary (Vander Pol, et al. 2005; Ham, et al. 1994), model sensitivity was conducted on this constraint (11A and 11B). Due to the fact that the crude protein constraint was not binding, eliminating the minimum urea constraint did not cause optimal DGS inclusion rates to change significantly. However, it did increase profits by as much as \$1.50/head within the DDGS model and by \$1.24/head within the WDGS model. Since the magnitude of these affects are largely driven by the price of urea, model sensitivity to the base \$361.50/ton was conducted. Results indicated that as long as crude protein was not binding, increasing or decreasing the price of urea did not impact optimal DGS inclusion rates (figures K1 and K2). However, once DGS inclusion levels dropped below 7% and crude protein became binding, optimal DGS inclusion rates increased by 1% to 2% when the price of urea was increased by 25%.

Sensitivity analysis to the maximum limestone constraint revealed that optimal DGS inclusion levels were not significantly affected. However, profit increased by as much as $0.43/head in the WDGS model and $0.32/head in the DDGS model over evaluated DGS/corn real price ratio scenarios. Conversely, tightening this constraint by 25% had the exact opposite effect on profit.

Additional Feed Ingredient Sensitivity Analysis

Due to the established base case prices (table 4), the model was choosing to incorporate corn silage as the primary roughage ingredient as opposed to hay in the majority of previously examined cases. However, in some areas of the country the reverse price scenario may apply. For this reason, the impact of including hay as the primary roughage ingredient on optimal DGS inclusion rates was examined by dropping the hay price to zero, thereby "forcing" the model to choose hay over corn silage. Again, optimal inclusion results were qualitatively equivalent to the base model, except when the DGS inclusion level dropped below 7% under high DGS/corn price ratios (figures L1 and L2). After which point the optimal DGS inclusion level decreased relative to the base model. This was due to the fact that after this point crude protein becomes a binding constraint. Since, hay contains more protein that corn silage (table 5), less DGS is required to fulfill the protein requirement when hay is included as the roughage ingredient. In summary, which roughage ingredient is incorporated within the ration does not significantly impact the economic substitutability of corn and DGS, until crude protein becomes binding (below 7% DGS inclusion). After which point, including hay within the diet as opposed to corn silage will reduce optimal DGS inclusion rates.

WDGS/DDGS Price Relationships

Thus far, a world where the producer has either WDGS or DDGS available to them has been modeled and the question has been asked: "what is the optimal percent dry matter to include in the feedlot ration?" However, some producers have both DGS types available and must choose both type and amount to include in their rations. Given that research trials have shown that WDGS are the more feed efficient DGS type, WDGS are generally preferred over DDGS. However, it has also been noted that it is more costly to transport WDGS due to its high moisture content, and there may also be increases in handling and storage costs (losses) associated with the feed. Additionally, the WDGS/DDGS purchase price ratio quoted at the ethanol plant may vary across time and space. The question then remains: "at what WDGS/DDGS real price ratio does it become economically efficient to switch from WDGS to DDGS"? Where again, "real" refers to the price after accounting for transportation, storage, and handling costs. Once the appropriate type of DGS is determined, the corresponding DGS/corn real price ratio and figure I1 or I2 can be used to identify the optimal quantity to include in the ration.

Figure M presents the amount by which the optimized profit per finished animal from the WDGS model exceeds that from the DDGS model across various WDGS/DDGS real price ratios. This assumes a DDGS/corn real price ratio of 1.0 and a corn real price of $2.78/bu. According to these results, the real WDGS/DDGS price ratio at which it becomes economical to switch from WDGS to DDGS is at about 1.29. Table

12 presents this economically optimal switching point under a variety of DDGS/corn real price ratios as well as various real corn prices. Under this array of price relationships the lowest WDGS/DDGS price ratio at which a producer would want to switch DGS types is at 1.23 and the highest is 1.38. When both the corn price and the DDGS/corn feed price ratio are at their historical maximums ($4.18/bu and 1.2, respectively), the WDGS/DDGS real price ratio at which it becomes economical to switch to DDGS is at 1.23. Conversely, when both the corn price and the DDGS/corn feed price ratio are at their historical minimums ($2.00/bu and 0.80, respectively), the WDGS/DDGS real price ratio triggering a switch from WDGS to DDGS occurs at 1.38.

When calculating the WDGS to DDGS real price ratio, there may be additional handling charges or storage losses incurred from feeding WDGS. This additional cost is likely to differ across operations. However, the question can be asked: "what does this additional cost have to be before a producer is indifferent between DDGS and WDGS?" While each case will be different, the following is an example of how table 12 might be used to help answer this question. Suppose producer A (same as presented above, on pg 57) facing zero DGS transport costs can get DDGS for $101.53/ton or WDGS for $33.84/ton (both equal $0.056/lb DM) and corn for $2.78/bu (as fed). Now suppose that this producer is incurring additional handling costs for feeding WDGS, or perhaps in another scenario the feedlot manager is penalizing WDGS to encourage the cattle owner to choose DDGS as their DGS grain source. How much additional handling cost would producer A economically be willing to accept before switching to DDGS, or in the alternative scenario how much would the feedlot manager have to penalize WDGS to encourage the cattle owner to choose DDGS? In this case a WDGS/DDGS real price ratio of 1.29 (the switching point for a DDGS/corn price ratio of 1.0 and a corn price of $2.78/bu) is reached when the real WDGS price is $0.072/ lb DM. Therefore, a $0.016/lb DM ($9.74/ton) increase in handling costs could be incurred before it would become economical to switch to DDGS.

(6.2.2) Alternative "Other Variable Cost" Parameters

Sensitivity analysis was also conducted on changes in the yardage cost and interest rate parameters. Given that each of these parameters are multiplied by the number of days on feed required to reach the targeted finish weight, having a higher yardage cost or a higher interest rate will penalize feed rations resulting in lower average daily gains. Since WDGS inclusion has a larger (positive) impact on ADG than DDGS, having a higher interest rate or yardage costs could theoretically alter the optimal ration as well as increase the WDGS/DDGS real price ratio at which it becomes economically efficient to switch from WDGS to DDGS. However, sensitivity analysis showed that 25% increases or decreases in these parameters did not qualitatively affect model results.[13]

(6.2.3) Alternative Manure Disposal Cost Scenarios

There are many assumptions underlying the manure disposal cost component of the model. This is why it is particularly important to examine model sensitivity to a few of the key assumptions made within this component. Table 13 illustrates the base case

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[13] While the model may not have been very sensitive to changes in these parameters; not accounting for how animal growth rates across various feed rations impacts overall profit significantly and alters the optimal feed ration.

parameters as well as the parameters used within eight scenarios analyzed within this sensitivity analysis. While this section will not attempt to analyze all possible combinations of scenarios, it will hopefully provide a heightened understanding of how incorporating manure disposal costs into the economic ration formulation affects optimal DGS inclusion results.

The first scenario represents a case where the feedlot has less access to land on which to dispose of manure. In other words, it represents a feedlot facing higher manure disposal costs. In this case there are only 250 acres accessible to the operator for manure disposal every mile. This is 50% of the 500 ac/mile accessible within the base model. Recall that accessible acres were defined within chapter five as being acres which the operator either owns or has access rights to use for manure disposal. DDGS and WDGS model results, comparing the base case results with scenario one, are shown within figures N1 and N2, respectively. Results indicate that decreasing the land available has relatively no impact on optimal WDGS inclusion. However, over the historical range of DDGS/corn feed price ratios there is a slight, 1.4% on average, decline in optimal DDGS inclusion rates when the land accessible was constrained to 250 ac/mile.

The second scenario (also illustrated within figures N1 and N2) represents a case where there are no manure disposal costs incorporated into ration formulation decisions. While there is no change in optimal WDGS inclusion levels over the historical WDGS/corn feed price ratio range, optimal inclusion rates increased by an average of 2.4% over the WDGS/corn price ratio range of 1.1 to 1.5. Within the DDGS model, inclusion increases by about 3.6% over its historical feed price range.

The third scenario considers speculations regarding future increases in corn acreage by examining an extreme case where 100% of the acres accessible to a given feedlot for manure disposal are corn acres. Figures O1 and O2 compare this scenario with the base case scenario. Note that scenario three does not have a qualitatively significant impact on model results for either DGS model.

The fourth scenario (also shown within figure O1 and O2) examines an alternative application rate scenario. Application rate scenario 'A', used within the base model, represents a scenario where the percentage breakdown of available crop acres in which the operator must apply at the nitrogen removal rate, the phosphorus removal rate, or which exceed soil phosphorus limits and are unavailable for manure disposal remains in constant proportion (40%, 40%, and 20%, respectively) as the producer travels further from the feedlot to dispose of the manure. Application rate scenario "B' represents a case where this percentage breakdown is not constant across hauling distance. Instead, the percentage of total acres in which manure can be applied shifts from the no application rate category (total lbs of P/ac exceed 300) to the phosphorus removal rate (total lbs of P/ac are between 150 and 300) to the nitrogen removal rate category (total lbs of P/ac are less than 150) as the producer is forced to haul manure further distances. While this scenario was developed after talking with producers, the exact shift in proportions implemented within the model is purely hypothetical and is illustrated within table 14. As illustrated in figures O1 and O2, changing the application rate scenario had very little impact on optimal DGS inclusion levels. This could be attributed to the fact that DGS are high in both protein and phosphorus; therefore, it doesn't really matter which application rate one is applying, in terms of how it affects the substitutability between DGS and corn.

The fifth scenario, illustrated within figures P1 and P2, examines a larger operation running 5,000 head. Since, total manure volume will increase, so will total manure disposal costs. This will penalize rations with higher phosphorus and crude protein compositions (i.e. DGS). Therefore, it is expected that, ceteris paribus, increasing the size of the operation will decrease the optimal DGS inclusion level. However, this statement makes the strong assumption that all other costs and prices remain constant, as it is likely that a larger operation will be able to negotiate price discounts (volume or contract based). Additionally, the larger firm may also have equipment that could make transport and general handling costs less costly. They may also be able to spread out any additional fixed costs, which have not been dealt with directly within this thesis other than the assumption stated on page 35 that all operations considered had the physical capital necessary to handle any DGS inclusion level. This being said, as illustrated within figure P1, optimal DDGS inclusion level decreases by an average of 4% over the DDGS/corn price ratio range of 0.8 to 1.1. Optimal WDGS inclusion also decreases by about 4% within scenario five (figure P2); however it decreases over the WDGS/corn price ratio range of 1.1 to 1.4.

The sixth scenario continues to examine the larger operation, but asks: "what would optimal DGS inclusion be if this larger operation was faced with disposing of its manure on ½ of the base case assumed landbase?" In essence, this scenario combines scenarios one and five. This scenario is also observed within figures P1 and P2, where a 5,000 head operation is assumed and only 250 acres of land every mile are accessible for manure application. In both models, DGS inclusion declined significantly over the base case. Optimal DDGS inclusion decreased by an average of 8% over the DDGS/corn real price ratio range of 0.8 to 1.2, and optimal WDGS inclusion declined by an average of 7% over a WDGS/corn real price ratio range of 0.9 to 1.4.

The seventh manure disposal cost scenario values the manure as opposed to the base case where this value was assumed to be zero. This scenario, illustrated within figures Q1 and Q2 values the nutrients within the manure (VN) based on weighted commercial fertilizer values for both P_2O_5 and nitrogen (recall that P_2O_5 is a converted form of phosphorus). This scenario accounts for the value of the nutrients within the manure as a source of crop nutrients. As shown in equation (26), the nutrient content of the manure was valued by summing the quantity of each nutrient excreted multiplied by its respective commercial fertilizer value. Commercial fertilizer values were assumed to be: \$0.25/lb P_2O_5 and \$0.40/lb nitrogen (Rausch 2006).[14] Valuing the manure significantly increases optimal DGS inclusion levels within both models. Over the DDGS/corn real price ratio range of 0.9 to 1.3, the optimal DDGS inclusion increased by an average of 11%. Whereas, over the WDGS/corn real price ratio range of 1.1 to 1.6, WDGS inclusion rates increased by about 9%.

(26) $VN = (0.40 * N_e) + (0.25 * P_2 0_5)$

The eighth and final scenario examines a case where only the nitrogen is valued. For many farms, soil phosphorus levels are likely to be sufficiently high to where only the nitrogen has any economic value. As illustrated within figures Q1 and Q2, solely valuing nitrogen decreases optimal DGS inclusion by about 1% to 2%, below results discussed for scenario seven.

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[14] Given that the model does not account for nitrogen volatilization, the value of nitrogen may be overestimated. Similarly, the costs of disposing of the nitrogen estimated within previous scenarios may have also been overestimated.

(6.2.4) Alternative Animal Response Function Parameters

A significant portion of what has driven model results thus far is the animal response functions assigned within each model. Recall that the parameters used within the average daily gain and dry matter intake functions were obtained using SUR estimation procedures, as described within chapter three (equations 11 and 12). However, as the data from the feeding trials revealed, there is a large degree of variation and a general lack of agreement regarding these coefficients and their significance. Therefore, it was deemed important to explore model sensitivity to alternative animal response function parameters. Stated differently, what would optimal DGS inclusion be under various levels of risk aversion regarding animal performance at various DGS inclusion levels? For instance, if the SUR estimates represent what is expected to happen on average, what would optimal inclusion be if one was not quite so optimistic with regards to the animal response function parameters? These evaluations can also be considered parameterizations of the model for producers of alternative risk aversion levels. For instance, a feedlot operator who is overly risk averse may utilize the "worst case" scenario in making decisions where a purely risk neutral producer may ignore these scenarios and rely solely on models utilizing SUR point estimated functions.

Alternative parameter estimates were obtained using a Krinsky-Robb bootstrapping approach. More specifically, by utilizing the estimated parameter vector and covariance matrix, 1,000 animal response function estimates were generated from 1,000 randomly drawn parameter vectors. The resulting series of 1,000 animal response function estimates were then used to estimate 1,000 optimal rations with 1,000 resulting profits. The series of resulting profits was then sorted from "best" to "worst."

When all of the base assumptions were held constant and the optimization model was run under the 1,000 simulated animal response function estimations, there was a resulting $15.06/head difference between the lowest and the highest optimized profits in the DDGS model. Additionally, the optimal DDGS inclusion level ranged from 8.2% to 29.7%, the average inclusion was 19.4% with a standard deviation of 4.4%. In order to further describe this variation in optimal DDGS inclusion levels, a histogram and cumulative distribution function of the optimal DDGS inclusion level results are presented in figure R. The majority of the time (54%) the optimal DDGS inclusion level is within approximately the 15% to 20% range. Twenty five percent of the time the optimal inclusion rate for DDGS is less than about 17%, 50% of the time this rate is less than about 18%, and 75% of the time it is less than about 22%.

When the 1,000 animal response function estimations were run in the WDGS model, there was a resulting $14.64/head difference in the full range of resulting profits. However, there was far less variation in the optimal WDGS inclusion rate results than there was in the optimal DDGS inclusion level results. Optimal WDGS inclusion levels ranged from 27.0% to 29.7%, with an average of 29.7% and a standard deviation of 0.21%. This lower variation in results between the two models is partially attributed to the fact that the standard deviations of the estimated X_{WDGS} coefficients were significantly less than those reported for the X_{DDGS} coefficients (equations 11 and 12). The remaining difference can be explained by the fact that the optimal WDGS inclusion level within the original base model, using the base animal response function estimations for ADG and DMI, was at the maximum DGS inclusion level of 29.7%, where further inclusion was being constrained by the fat constraint (table 9). More specifically, even when the model was run under more favorable animal response function estimations (e.g. lower feed to gain ratios), the optimal WDGS inclusion level was unable to increase beyond this 29.7%. Additionally, while a decrease in the optimal WDGS inclusion level is expected under less favorable animal response function estimations, such a decline did not frequently occur.

Given that the fat constraint is preventing any variation within the above WDGS model results and the economical incentive to allow for a ration with higher fat content, sensitivity analysis to the estimated animal response function was also conducted using the relaxed fat constraint of 7.5%. Recall that when the fat constraint was increased by 25% and the base model price scenario was analyzed; neither the optimal DDGS inclusion level nor the optimal WDGS inclusion level was at its nutritionally constrained maximum (tables 11a and 11b). Therefore, relaxing these constraints should allow for increased variation in optimal DGS inclusion level results under an array of estimated animal response functions.

When this fat constraint was relaxed by 25% (i.e. the fat constraint = 7.5%), the range in optimal DDGS inclusion rates increased. Under this scenario, the optimal DDGS inclusion level ranged from 8.2% to 48.9%, the average inclusion was 19.7%, and the standard deviation was 5.6%. The histogram and cumulative distribution function of optimal DDGS inclusion level results under this scenario are presented within figure S. This analysis is very similar to that presented within figure R; however, this time the range of optimal DDGS inclusion rate results have been extended.

As expected, the variation in both optimized profit and optimal WDGS inclusion rates also increased under the relaxed fat constraint scenario. The resulting difference in optimized profit between the "worst" and "best" cases was \$18.34/head when such a procedure was run in the WDGS model. The optimal WDGS inclusion rate ranged from 27.1% to 48.9%, with a mean of 33.8% and a standard deviation of 5.3%. Figure T presents the histogram and cumulative distribution function of optimal inclusion level results. A large percentage of the time (74%) the optimal WDGS inclusion rate is within the 30% to 35% range; optimal inclusion is less than 30% only about 3% of the time and is greater than 35% about 23% of the time.

As expected, results within the WDGS model varied significantly more when the fat constraint was relaxed. Thus, the 29.7% optimal inclusion level for WDGS is insensitive to chosen animal response functions when the fat constraint is set at 6% of daily dry matter. However, when this constraint is relaxed by 25%, the optimal inclusion rate is between 30% and 35% the majority of the time. Furthermore, while the range in optimal DDGS inclusion increases when this constraint is relaxed, the inclusion rate remains at about 15% to 20% most of the time.

This sensitivity exercise illustrates the importance of taking animal response functions and associated variability into consideration when identifying optimal DGS inclusion rates. It is also "new", in the sense that it has not been previously applied, to the best of my knowledge, within a ration formulation context. However, it highlights the importance of recognizing the fact that reliance on a single set of animal response parameters can significantly alter economically optimal rations. Additionally, assuming a single set of animal response functions would assume that the nutrient value of all DGS are equal, which has been illustrated within table 1 as being a naïve assumption. Also, there are many other factors that underlie the true animal response function (e.g. breed, environmental condition, and stress). With all of the factors, which are nearly impossible to control within a single animal response function designed for broad application, identifying and analyzing the risk in using a single set of estimation parameters is vitally important.

CHAPTER 7: CONCLUSIONS

The rapid expansion of the ethanol industry has significantly altered the feeding landscape of the feedlot industry. Many feedlot operators are becoming increasingly concerned as to the extent of the impact that the rising demand for corn will have on their future feed costs. However, the by-product of ethanol production, distiller's grains, which can serve as a partial substitute within feedlot rations, has the potential to partially offset these rising feed costs.

Subsequently, a great deal of literature has been dedicated to identifying the appropriate inclusion rate of distiller's grains in feedlot rations. However, most currently prevailing recommendation rates fail to consider many economic variables, are strictly biologically based, and frequently reference only one feeding trial. The research presented within this thesis has illustrated the impacts of not taking these factors into account. Results indicate that commonly recommended DGS inclusion rates, often in the range of 30% to 40%, accurately reflect the economically optimal ration only under select scenarios. In fact, over the historically reported WDGS/corn feed price ratio range (0.74 to 1.01) the economically optimal WDGS inclusion rate remained at about 30%, while optimal DDGS inclusion rates ranged from 8% to 30% over its range of historically reported DDGS/corn feed price ratio range of 0.78 to 1.24. Notice that a significant portion of the time, these optimal rates are outside of the 30% to 40% commonly reported in the literature.

In addition to the price relationship between DGS and corn, the relationship between real WDGS and DDGS prices was also examined. This allowed for the trade-off between the feed efficiency of the WDGS and the transportation and/or storage and handling cost benefits associated with DDGS to be analyzed. Results indicated that under most DDGS/corn real price ratio and corn real price scenarios, the WDGS/DDGS real price ratio at which it becomes economically efficient to switch from WDGS to DDGS is between about 1.25 and 1.33.

Given that in the real world other parameters, besides feed costs, are also likely to vary from established base assumptions, sensitivity analyzes were conducted to identify additional determinants of optimal DGS inclusion rates. Sensitivity analyzes that were found to significantly affect these optimal rates included: the fat constraint, whether or not manure disposal costs were incorporated into cost calculations, whether or not the nutrients within the manure were valued at commercial fertilizer values, the size of the operation, and the estimated animal response functions incorporated into the model.

Relaxing the fat constraint from 6% to 7.5% increased the economically maximum DGS inclusion rate (i.e. optimal inclusion even when DGS were considered to be 'free') from 30% to 41%. With this higher fat constraint the probability that optimal WDGS inclusion rates were within the cited 30% to 40% increased over the base model with an imposed fat constraint of 6%. However, optimal DDGS inclusion rates remained below this range.

Not incorporating manure disposal costs increased optimal DGS inclusion rates by as much as 6.6% (DDGS model; DDGS/corn price ratio = 1.0). While valuing the nutrients increased optimal DGS inclusion rates by as much as 17% (DDGS model; DDGS/corn price ratio of 1.1). Increasing the size of the operation increased total manure volume, decreasing optimal inclusion rates by as much as 6.8% (DDGS Model;

DDGS/corn price ratio of 0.9). However, it was noted that other benefits of being a larger operation, such as possible price discounts, were not taken into account.

Given the importance of the estimated animal response function driving the model, sensitivity analysis was conducted on these estimates. Results indicated that optimal DDGS inclusion rates varied by greater degrees ranging from 8% to 30% across the base case scenario, while optimal WDGS inclusion rates remained close to 30%. Therefore, producers facing real price ratios in this range are justified in establishing a consistent WDGS inclusion rate within their rations; whereas changes in the DDGS/corn price ratio may lead to economically optimal ration alterations. Then again, there is a trade-off between what is economically optimal and having a consistent ration. This trade-off was examined by Coffey (2001); however, it was not examined within the scope of this thesis.

In order to determine these economically optimal DGS inclusion rates, a mathematical optimization model was developed, and while an array of often omitted factors were taken into account, further research would allow for a more complete model to be developed. First, estimations of marbling scores across DGS inclusion levels concluded that the DGS inclusion level was a statistically insignificant variable. However, given the limited data available, further research is needed. Second, the disposal costs for nitrogen as well as the value of nitrogen may have likely been overestimated, as nitrogen volatilization was not incorporated. Further information is needed regarding volatilization levels at various DGS inclusion levels before such a variable can be directly taken into account. Third, the price variation issue addressed by Coffey (2001), where the trade-off between having a consistent ration and having an optimal ration is incorporated, would also enhance the model. Fourth, more information is needed regarding how DGS inclusion affects animal; these animal response functions should be continually updated as new data becomes available. Also, response function estimation for specific growth stages would also prove useful. This would allow for multiple rations to be formulated across the time. Additionally, such information would allow for optimal finished weight to be calculated, following the methodology outlined by Boys, et al. (2007) when they determined the optimal slaughter weights of pigs. Finally, other factors affecting optimal DGS inclusion, which have recently come into light, have not been directly incorporated, including but not limited to: microtoxins, odor affects, and the use of certain antibiotics within the ethanol production process. However, in some instances a value/cost might be assigned to these other factors and incorporated as feed costs.

These sensitivity analyzes indicate the importance of taking all economic and animal response function parameters into consideration when identifying optimal DGS inclusion rates. Additionally, the model serves as a useful tool for analyzing optimal DGS inclusion levels under a wide range of plausible scenarios, and while the full range of these scenarios have not been exhausted, model results under a variety of circumstances have been presented. While this thesis has focused on the beef industry, and more specifically on the feedlot segment, the general methodological approaches would be useful for other species and or segments as well. Identifying optimal DGS inclusion rates under various price scenarios for the various species and industry segments would then allow for a more complete DGS demand estimation.

APPENDICES

APPENDIX A: FIGURES

Figure A: Corn Utilized in Ethanol Production

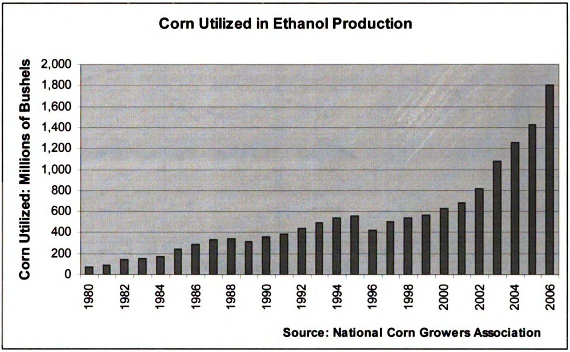


Figure B1: Meta-Analysis Data Trial Plots - DDGS Inclusion Rate vs. Feed to Gain

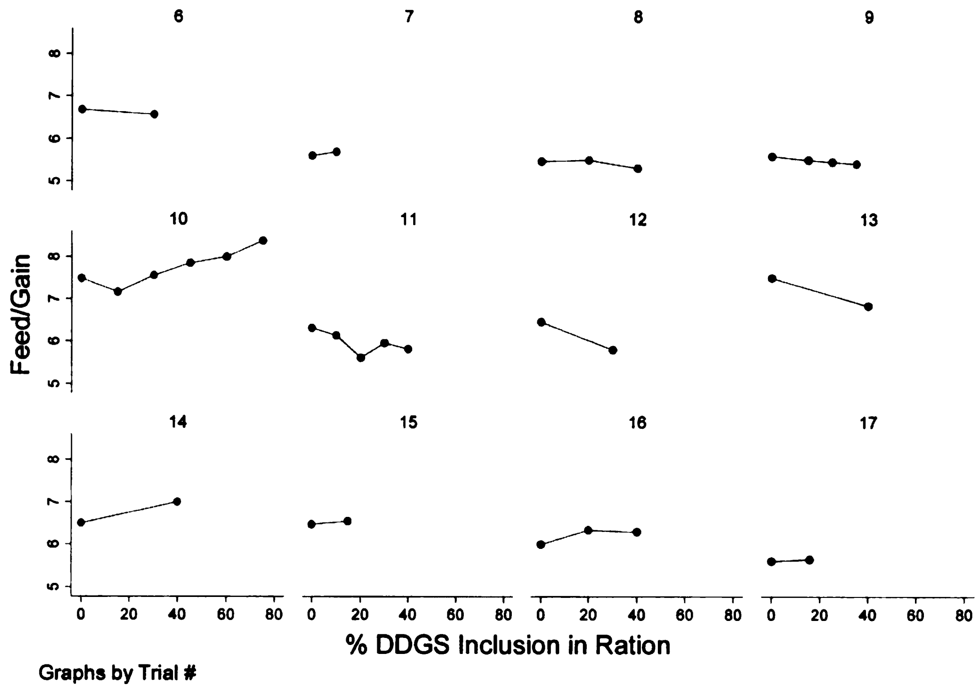


Figure B2: Meta-Analysis Data Trial Plots - WDGS Inclusion Rate vs. Feed to Gain

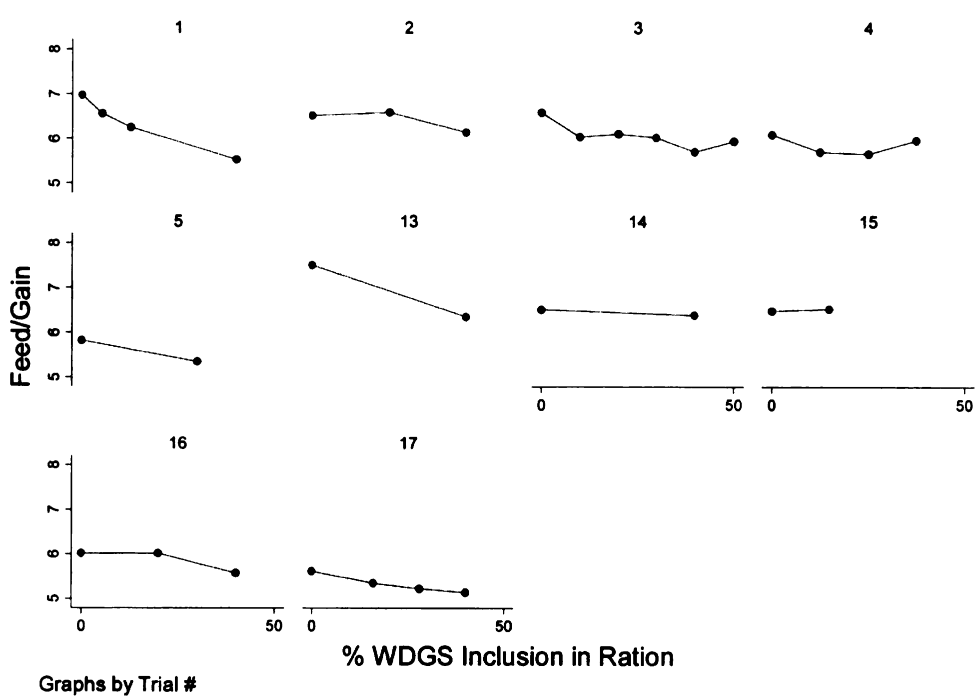


Figure C1: Meta-Analysis Data Trial Plots - DDGS Inclusion Rate vs. Average Daily Gain

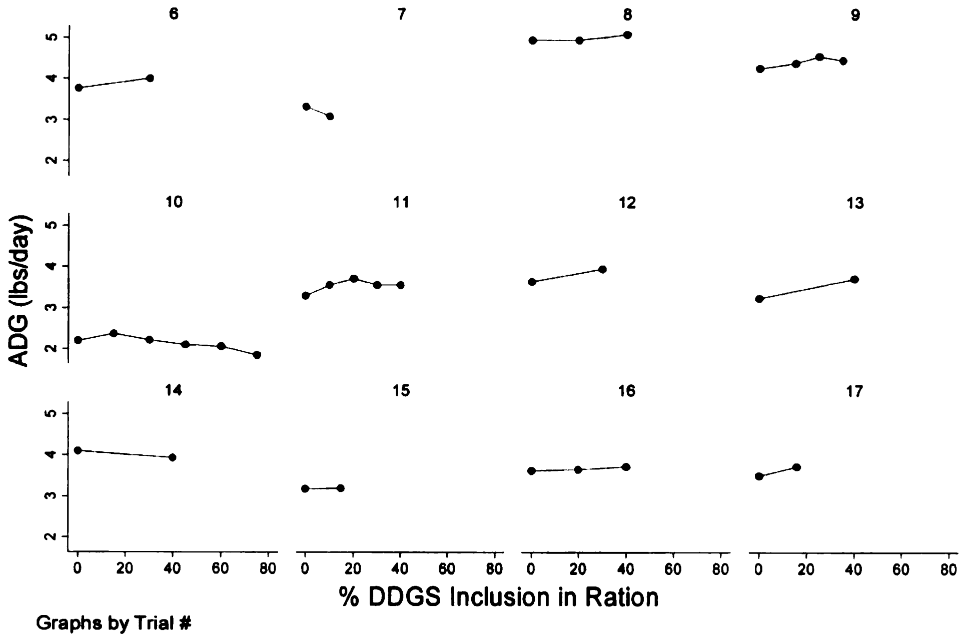


Figure C2: Meta-Analysis Data Trial Plots - WDGS Inclusion Rate vs. Average Daily Gain

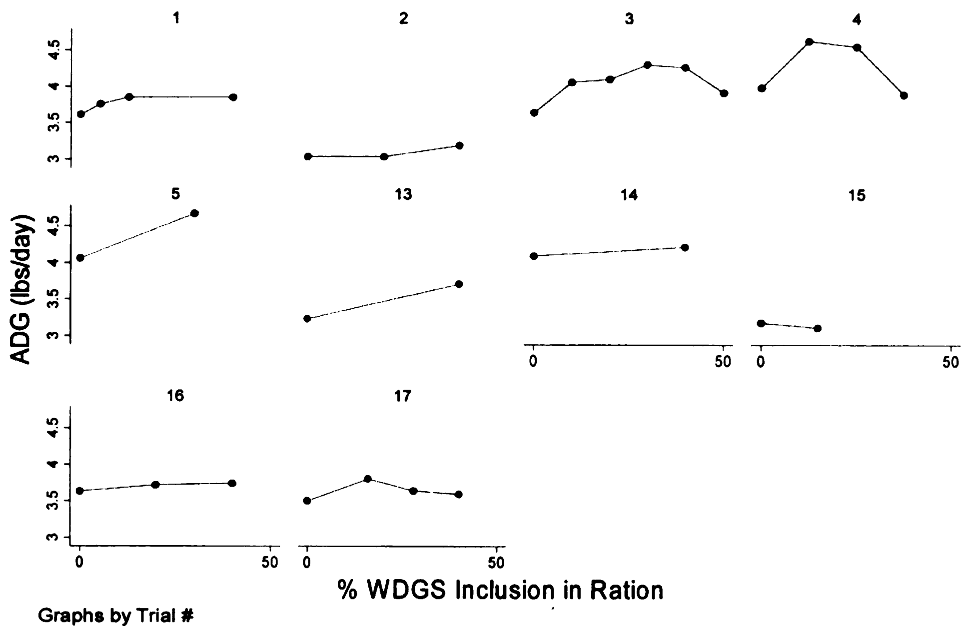


Figure D1: Meta-Analysis Data Trial Plots - DDGS Inclusion Rate vs. Dry Matter Intake

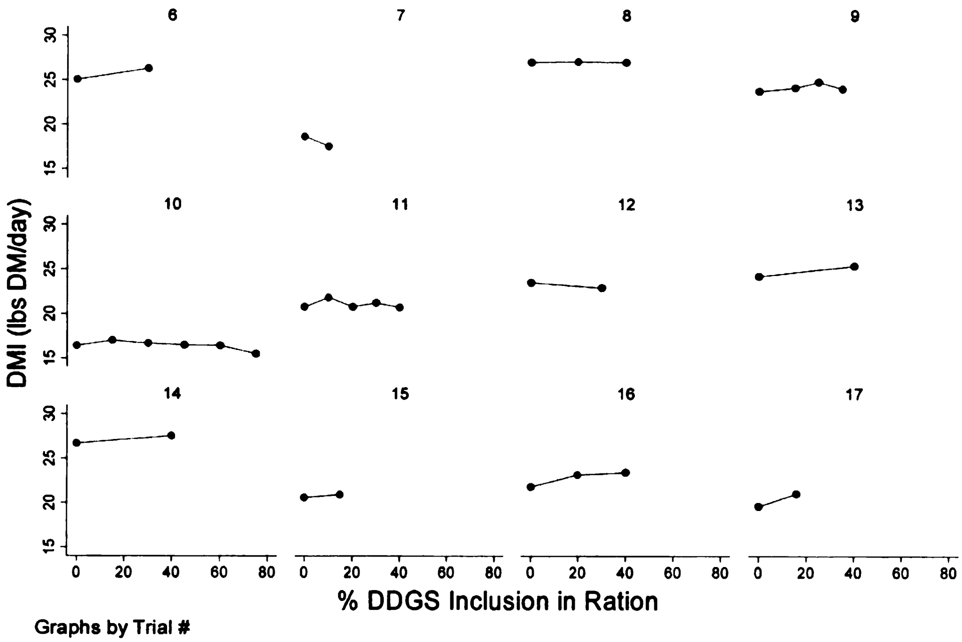


Figure D2: Meta-Analysis Data Trial Plots - WDGS Inclusion Rate vs. Dry Matter Intake

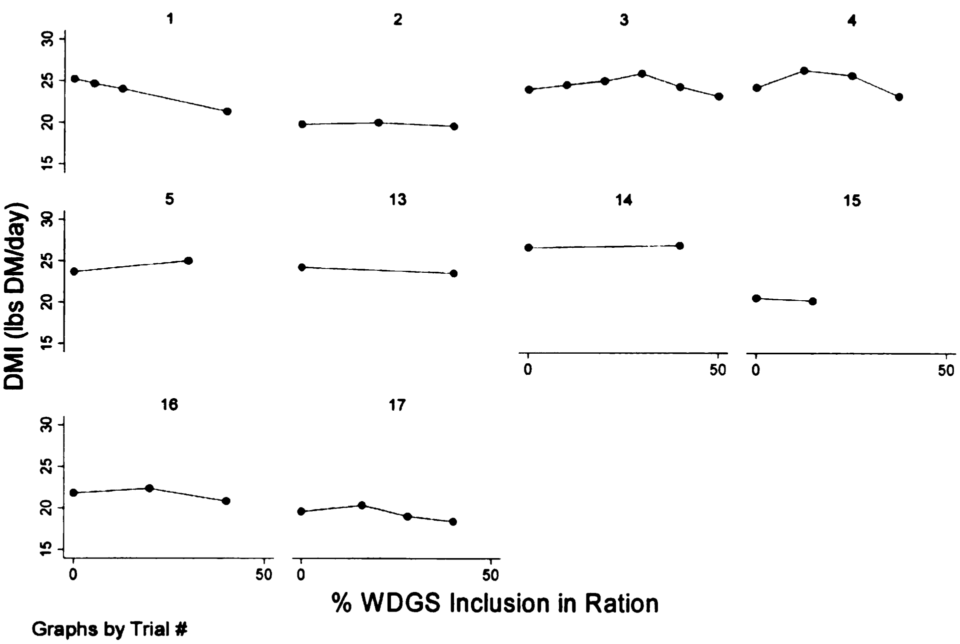


Figure E1: Meta-Analysis Data Trial Plots - DDGS Inclusion Rate vs. Marbling

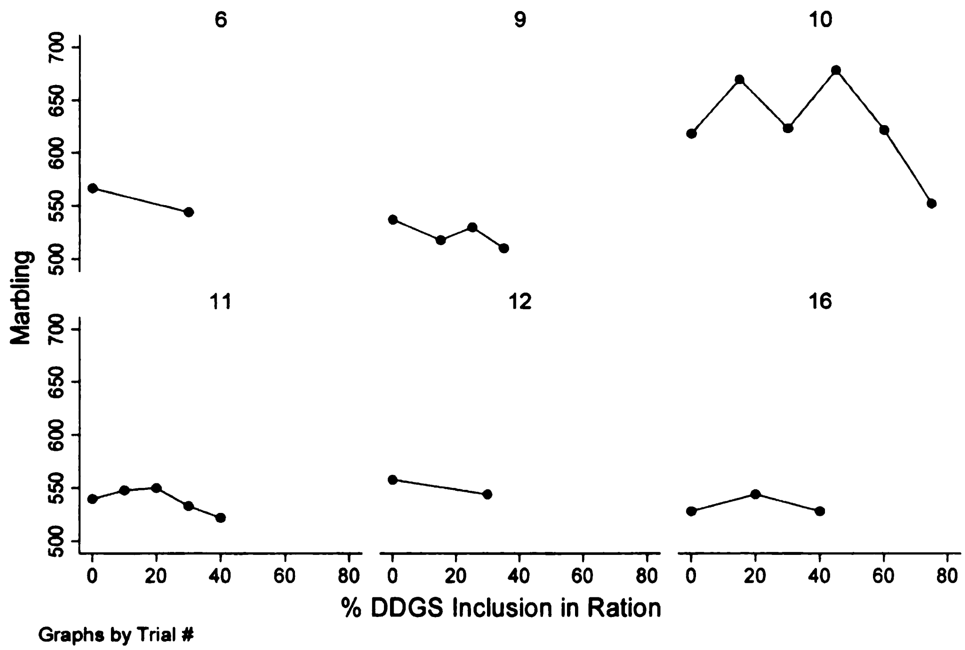


Figure E2: Meta-Analysis Data Trial Plots - WDGS Inclusion Rate vs. Marbling

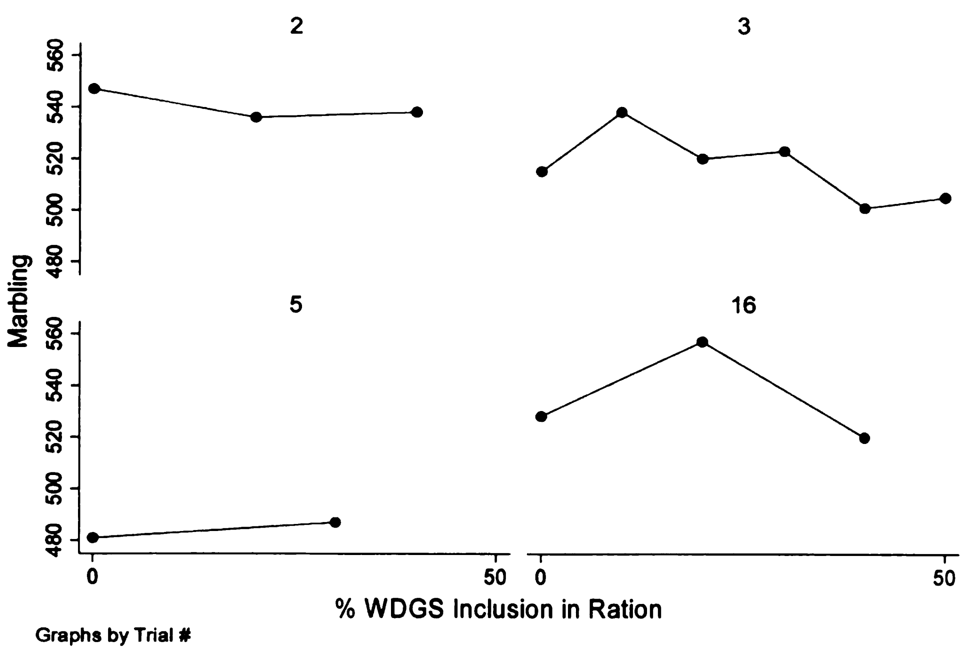


Figure F: Average Daily Gain at Various Distiller's Grain with Solubles Inclusion Levels

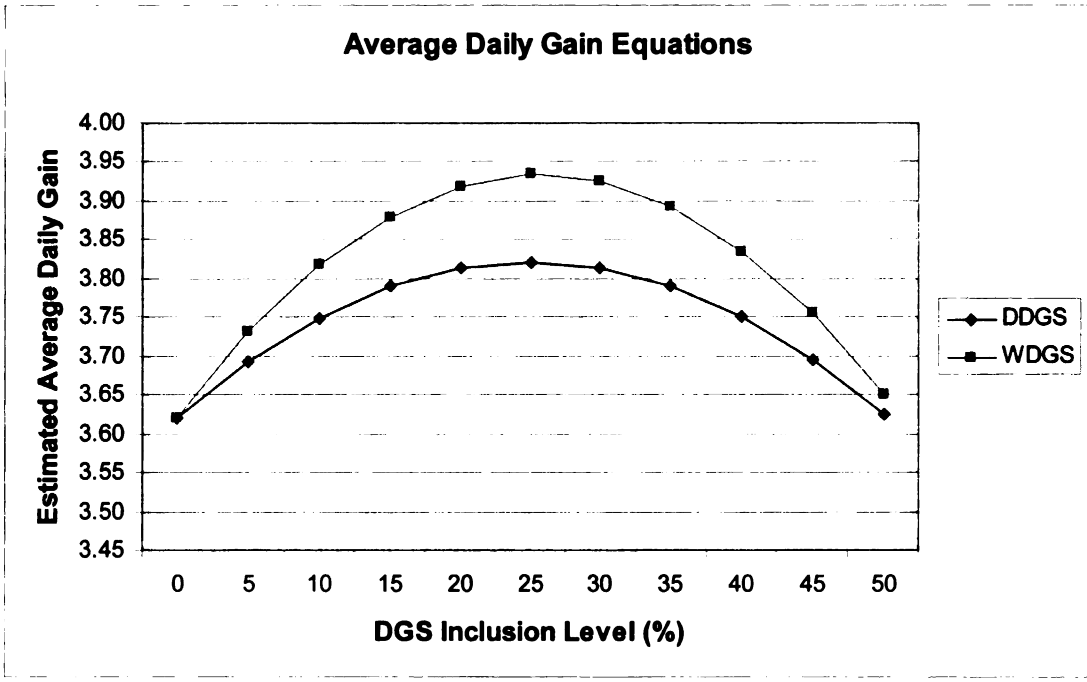


Figure G: Dry Matter Intake at Various Distiller's Grain with Solubles Inclusion Levels

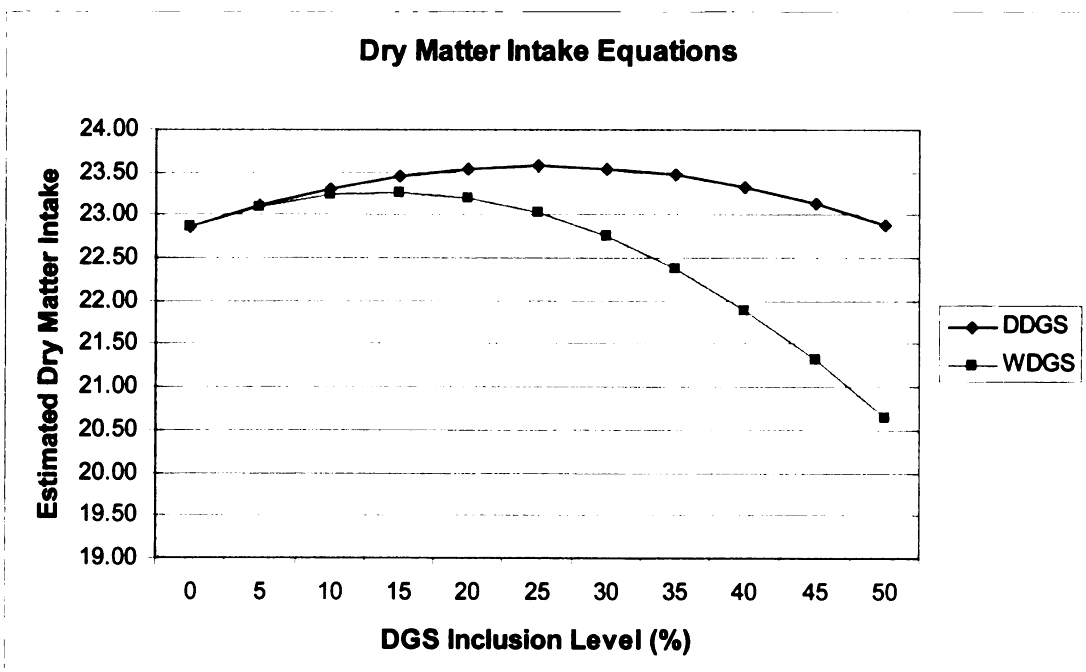
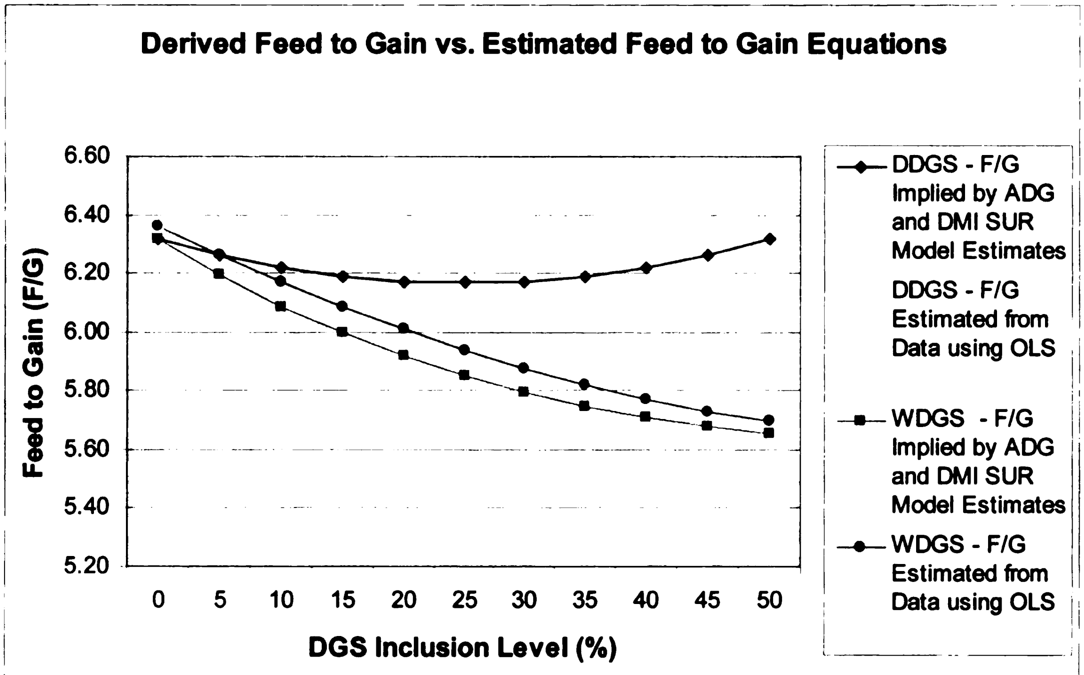
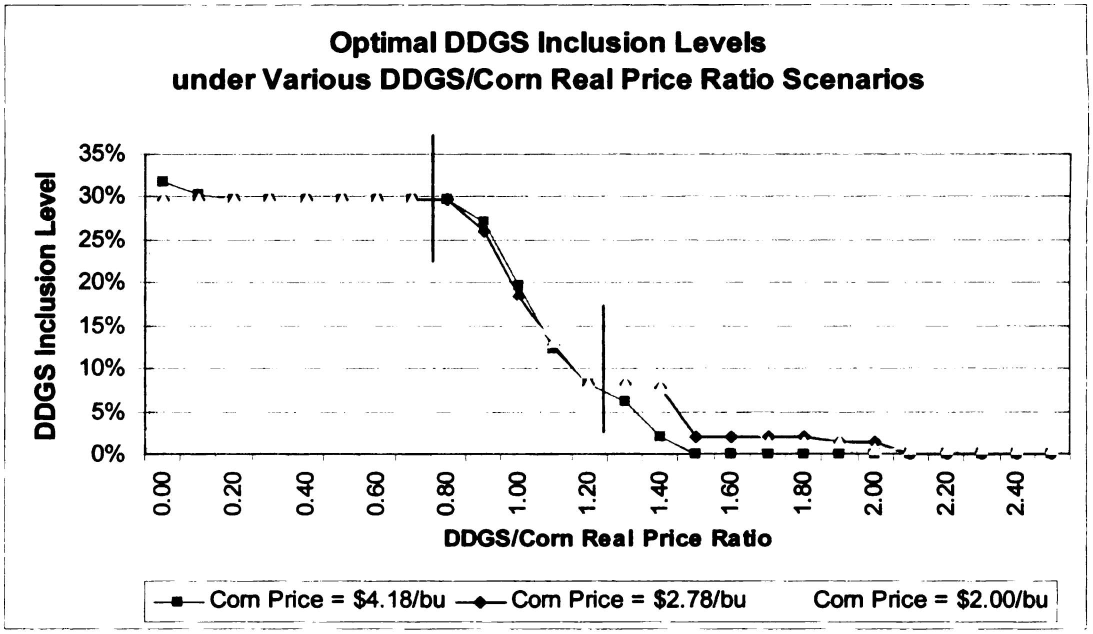


Figure H. Derived Feed to Gain vs. Estimated Feed to Gain Equations



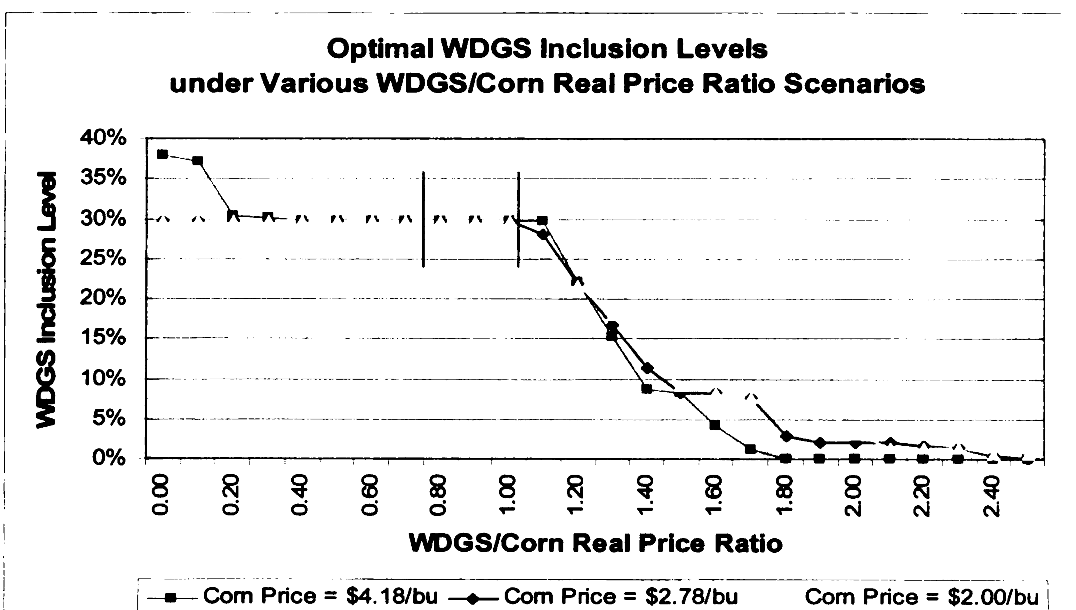
Note: DDGS inclusion was not found to have a statistically significant affect on feed to gain, and only a linear relationship between WDGS and feed to gain was significant.

Figure I1: Optimal DDGS Inclusion Levels under Various DDGS/Corn Real Price Ratio Scenarios



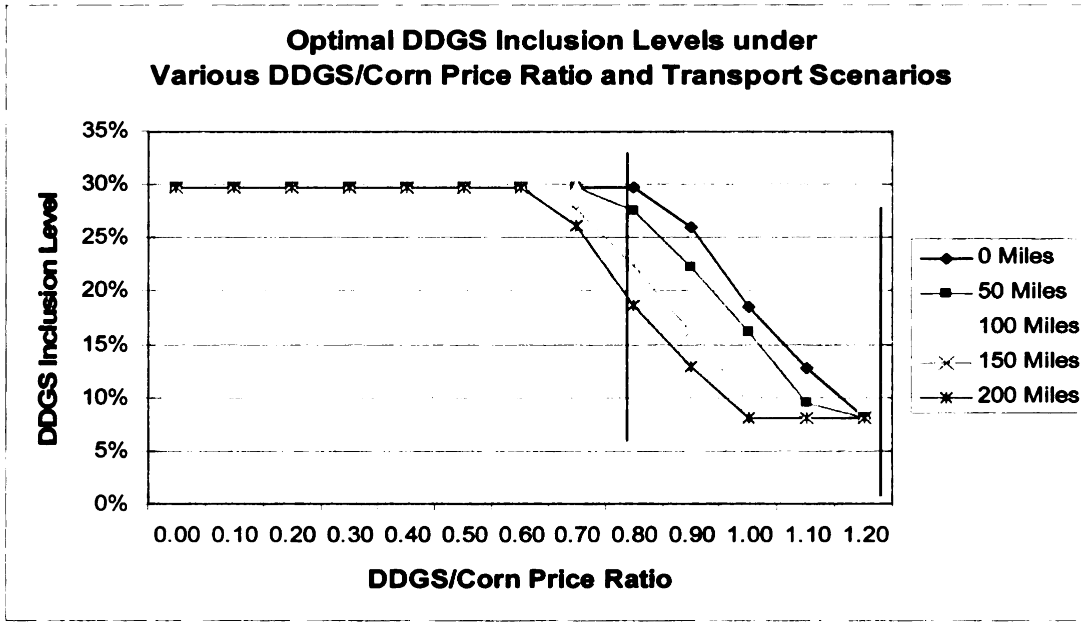
*Hash marks show range of historical DDGS/corn feed price ratios, based out of Chicago, IL (February 2006 – March 2007; LMIC).

Figure I2: Optimal WDGS Inclusion Levels under Various WDGS/Corn Real Price Ratio Scenarios



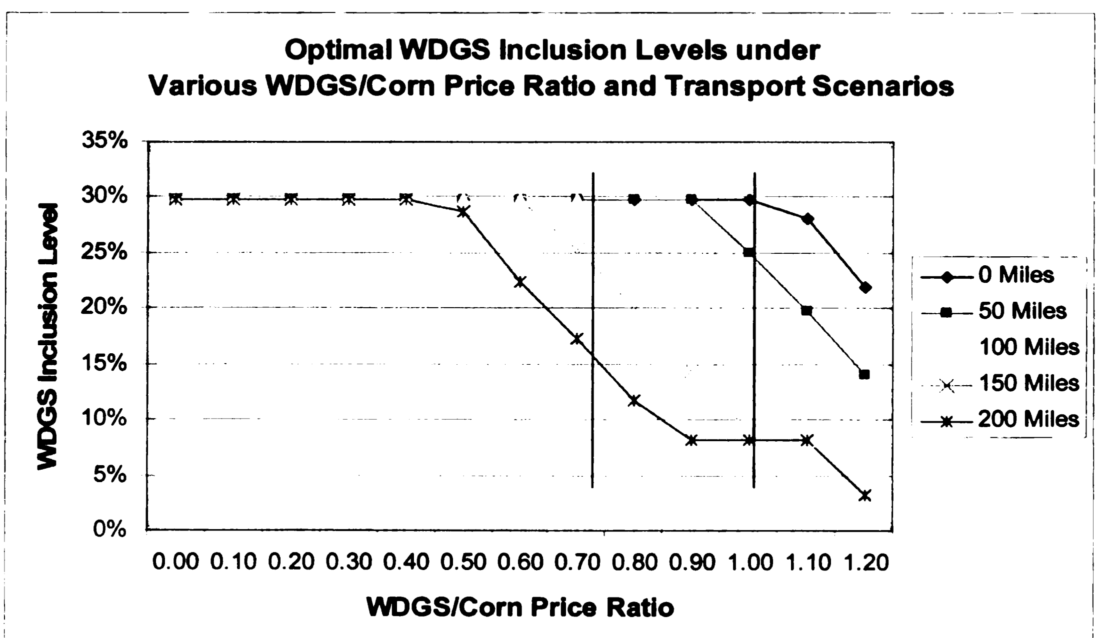
*Hash marks show range of historical WDGS/corn feed price ratios, based out of Chicago, IL (February 2006 – March 2007; LMIC).

Figure J1: Optimal DDGS Inclusion Levels under Various DDGS/Corn Price Ratio and Transport Scenarios



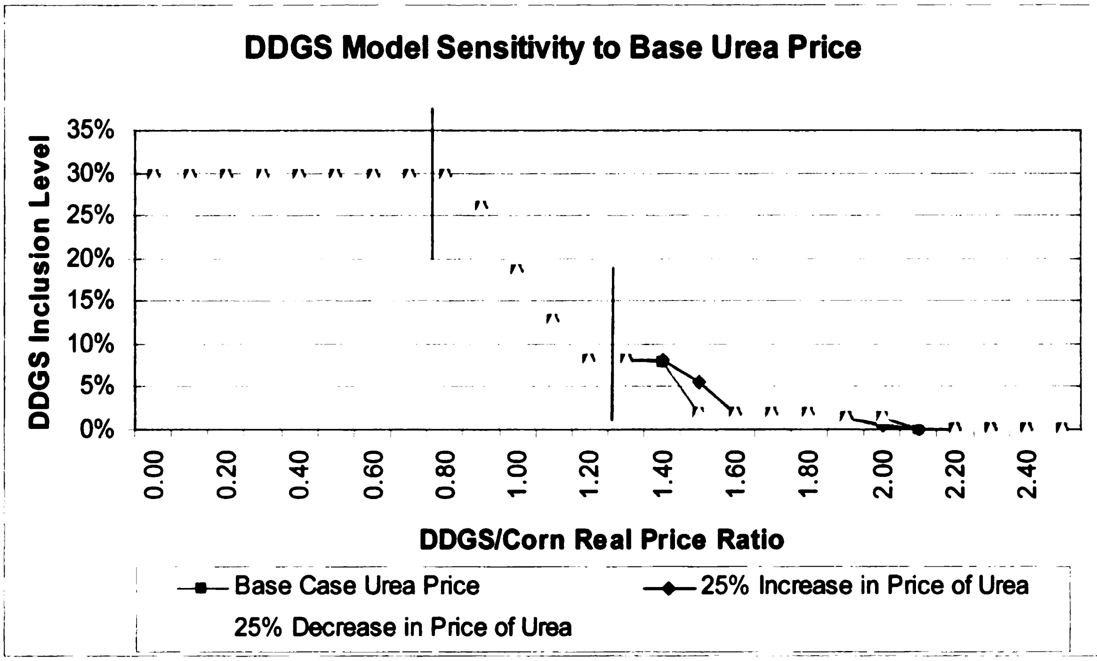
*Hash marks show range of historical DDGS/corn feed price ratios, based out of Chicago, IL (February 2006 – March 2007; LMIC).

Figure J2: Optimal WDGS Inclusion Levels under Various WDGS/Corn Price Ratio and Transport Scenarios



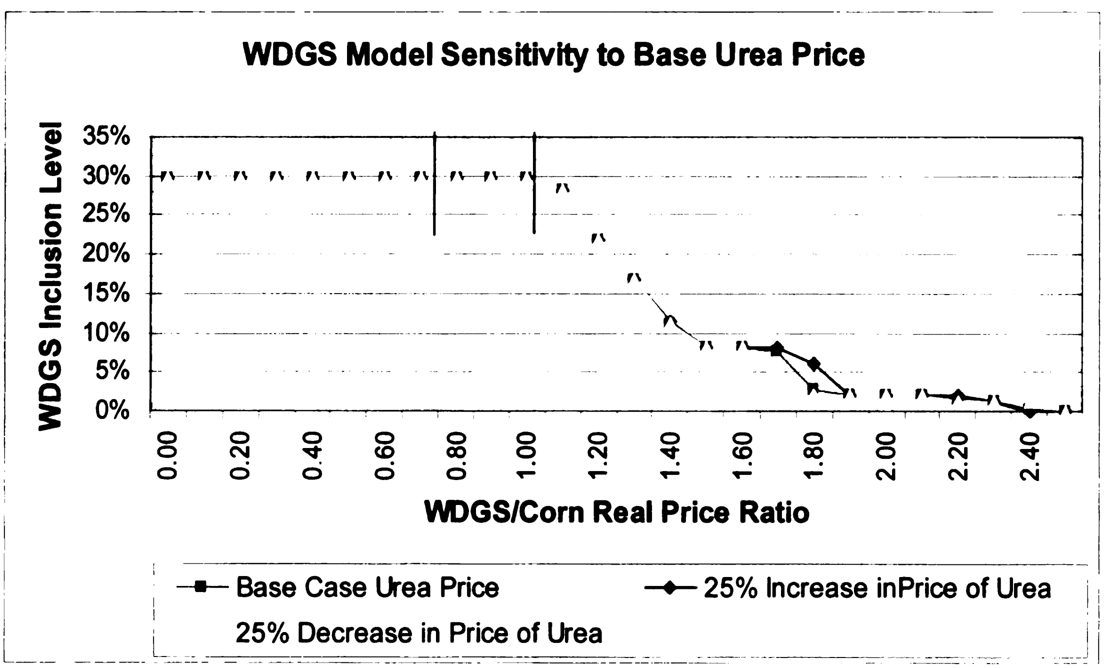
*Hash marks show range of historical WDGS/corn feed price ratios, based out of Chicago, IL (February 2006 – March 2007; LMIC).

Figure K1: DDGS Model Sensitivity to the Base Urea Price



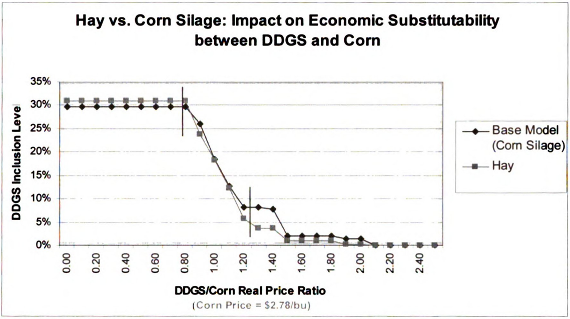
*Hash marks show range of historical DDGS/corn feed price ratios, based out of Chicago, IL (February 2006 – March 2007; LMIC).

Figure K2: WDGS Model Sensitivity to the Base Urea Price



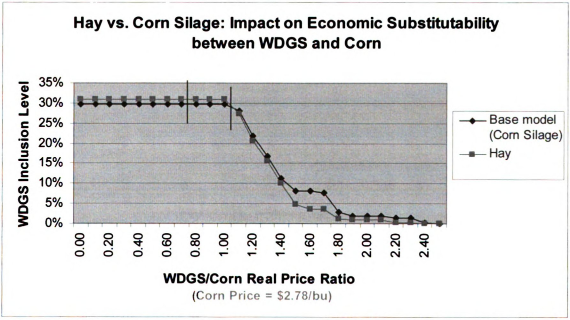
*Hash marks show range of historical WDGS/corn feed price ratios, based out of Chicago, IL (February 2006 – March 2007; LMIC).

Figure L1: Hay vs. Corn Silage: Impact on Economic Substitutability between DDGS and Corn



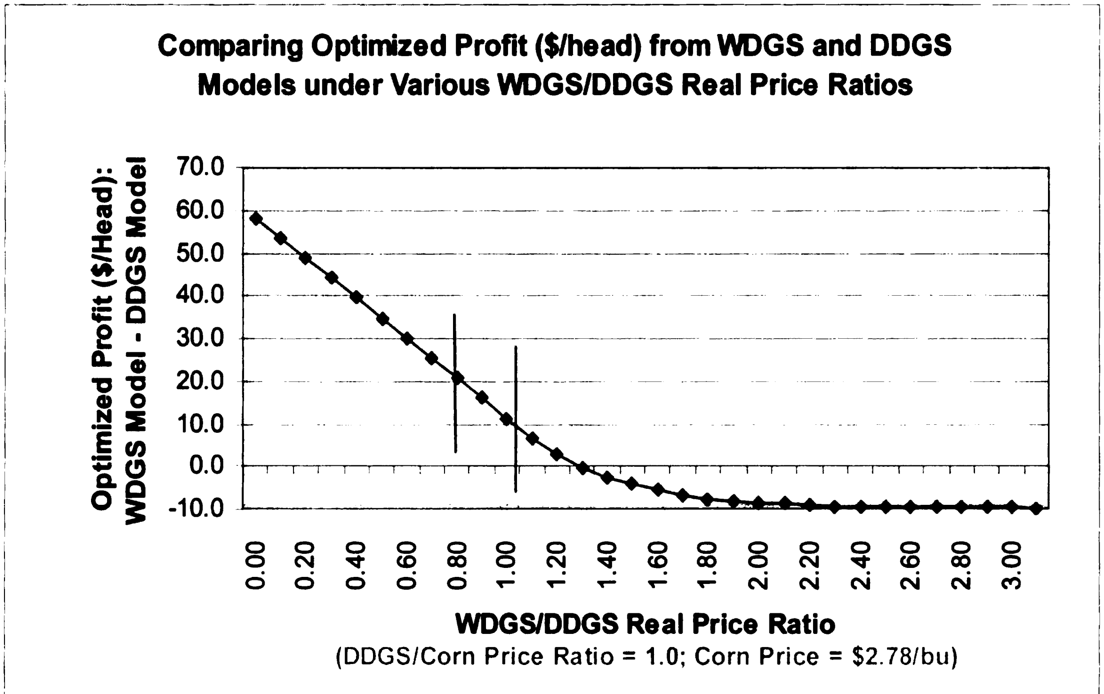
*Hash marks show range of historical DDGS/corn feed price ratios, based out of Chicago, IL (February 2006 – March 2007; LMIC).

Figure L2: Hay vs. Corn Silage: Impact on Economic Substitutability between WDGS and Corn



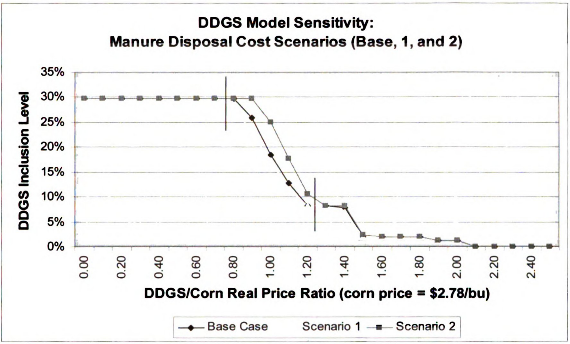
*Hash marks show range of historical WDGS/corn feed price ratios, based out of Chicago, IL (February 2006 – March 2007; LMIC).

Figure M: Analyzing the Profit Trade-Off between WDGS and DDGS under Various WDGS/DDGS Price Ratios



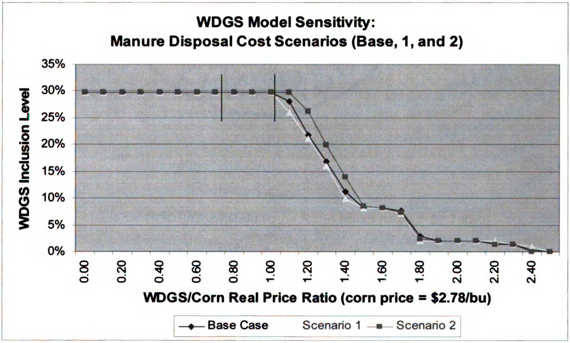
*Hash marks show range of historical WDGS/DDGS feed price ratios, based out of Chicago, IL (February 2006 – March 2007; LMIC).

Figure N1: DDGS Model Sensitivity: Manure Disposal Cost Scenarios 1 & 2



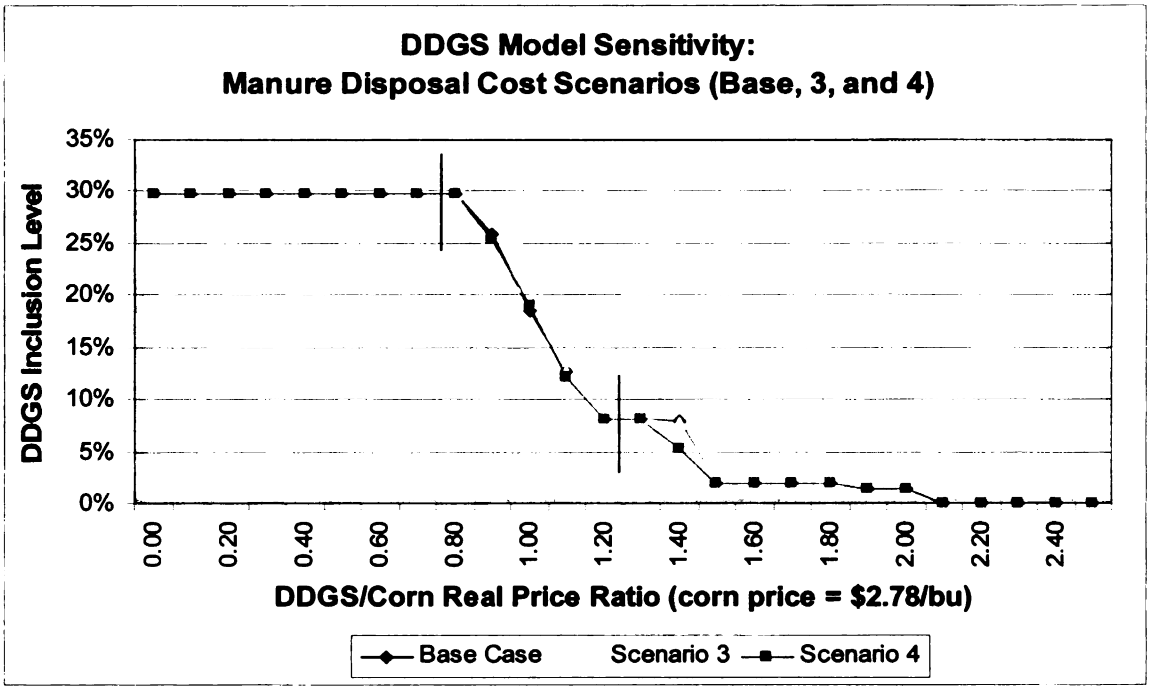
*Hash marks show range of historical DDGS/corn feed price ratios, based out of Chicago, IL (February 2006 – March 2007; LMIC).

Figure N2: WDGS Model Sensitivity: Manure Disposal Cost Scenarios 1 & 2



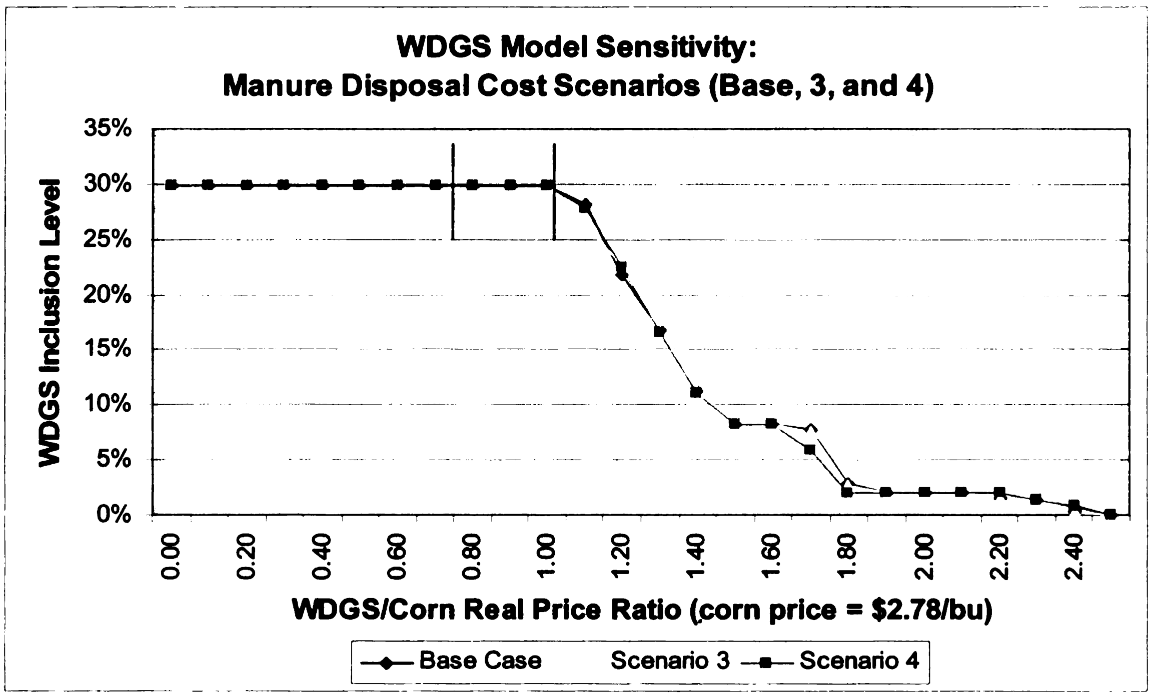
*Hash marks show range of historical DDGS/corn feed price ratios, based out of Chicago, IL (February 2006 – March 2007; LMIC).

Figure O1: DDGS Model Sensitivity: Manure Disposal Cost Scenarios 3 & 4



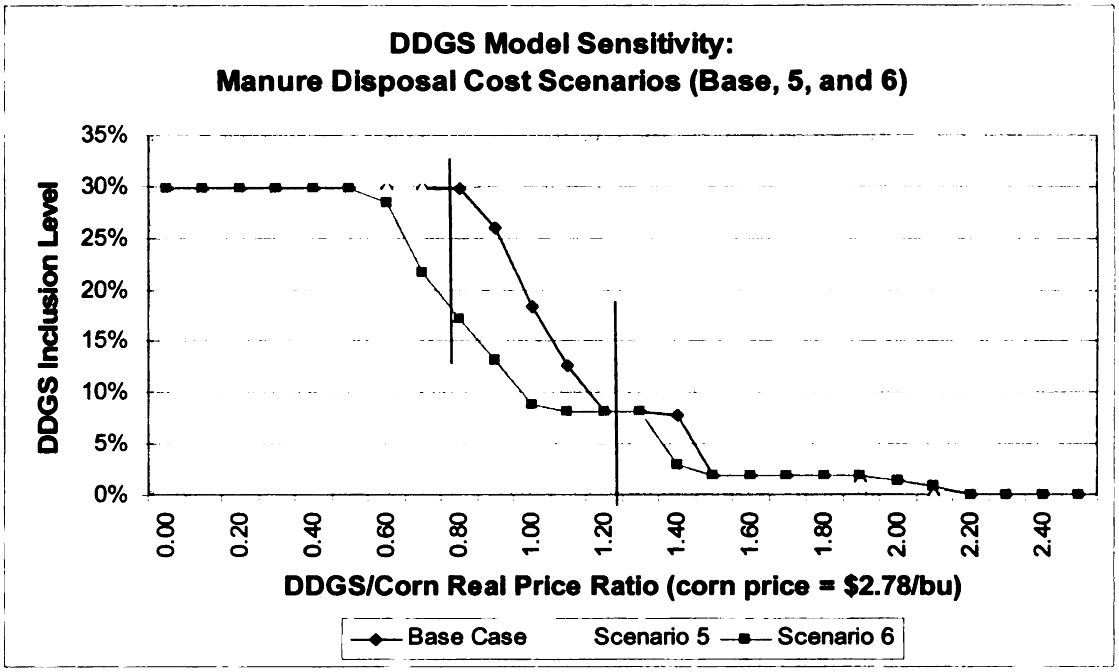
*Hash marks show range of historical DDGS/corn feed price ratios, based out of Chicago, IL (February 2006 – March 2007; LMIC).

Figure O2: WDGS Model Sensitivity: Manure Disposal Cost Scenarios 3 & 4



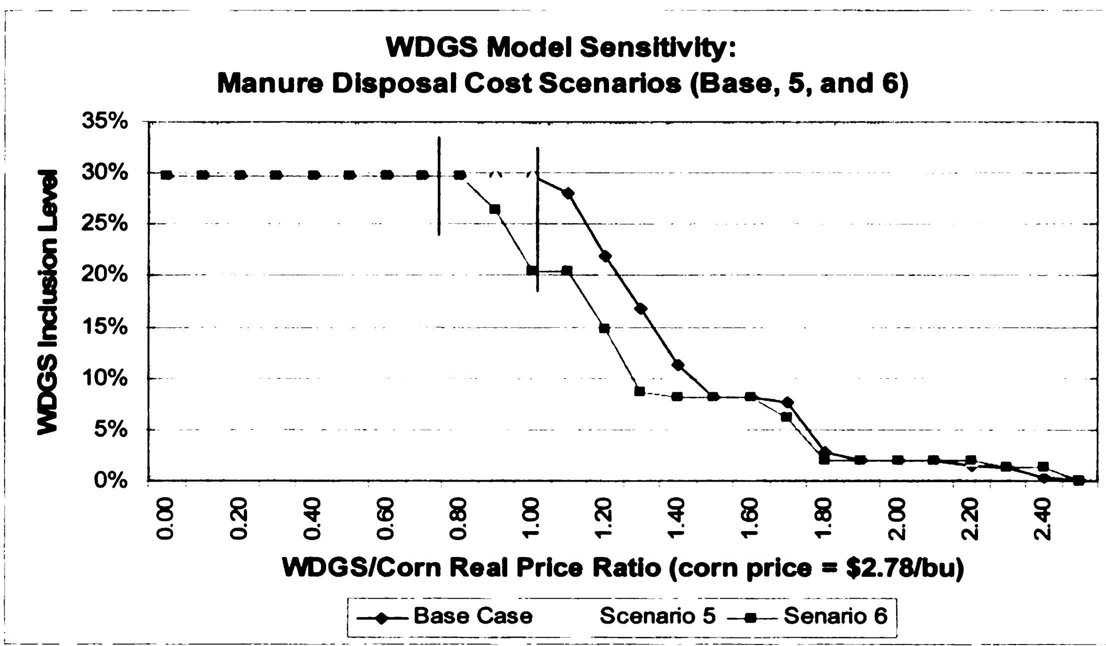
*Hash marks show range of historical DDGS/corn feed price ratios, based out of Chicago, IL (February 2006 – March 2007; LMIC).

Figure P1: DDGS Model Sensitivity: Manure Disposal Cost Scenarios 5 & 6



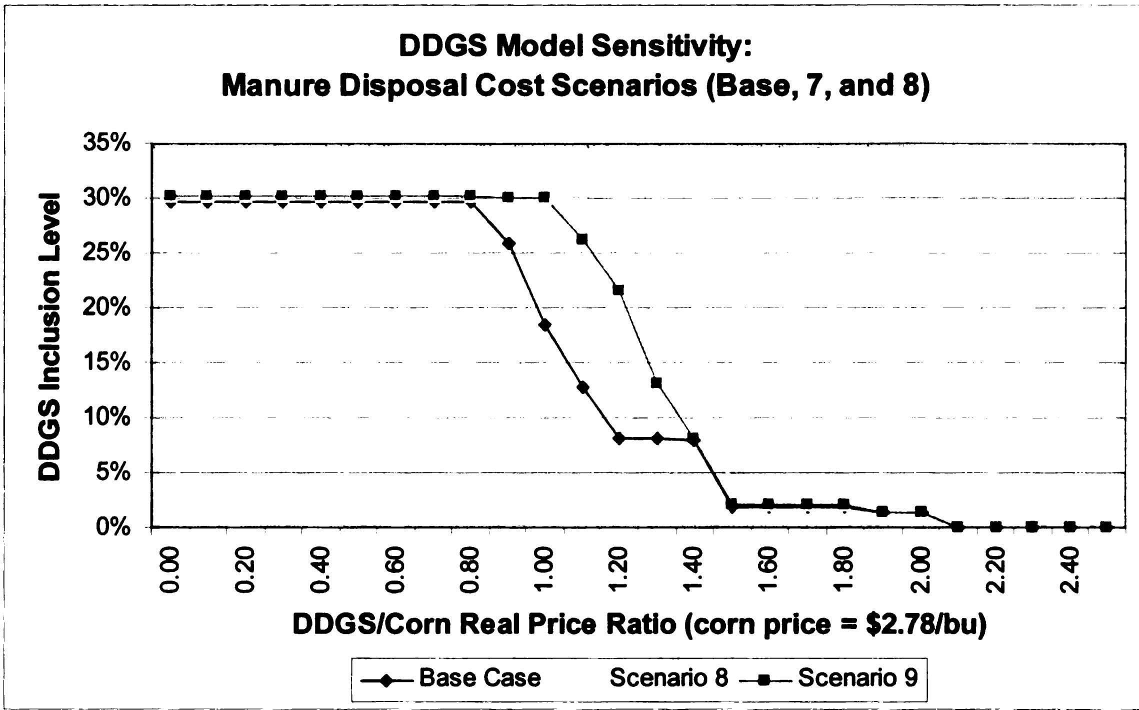
*Hash marks show range of historical DDGS/corn feed price ratios, based out of Chicago, IL (February 2006 – March 2007; LMIC).
**This assumes that all other parameters are held constant (e.g. output price, storage).

Figure P2: WDGS Model Sensitivity: Manure Disposal Cost Scenarios 5 & 6



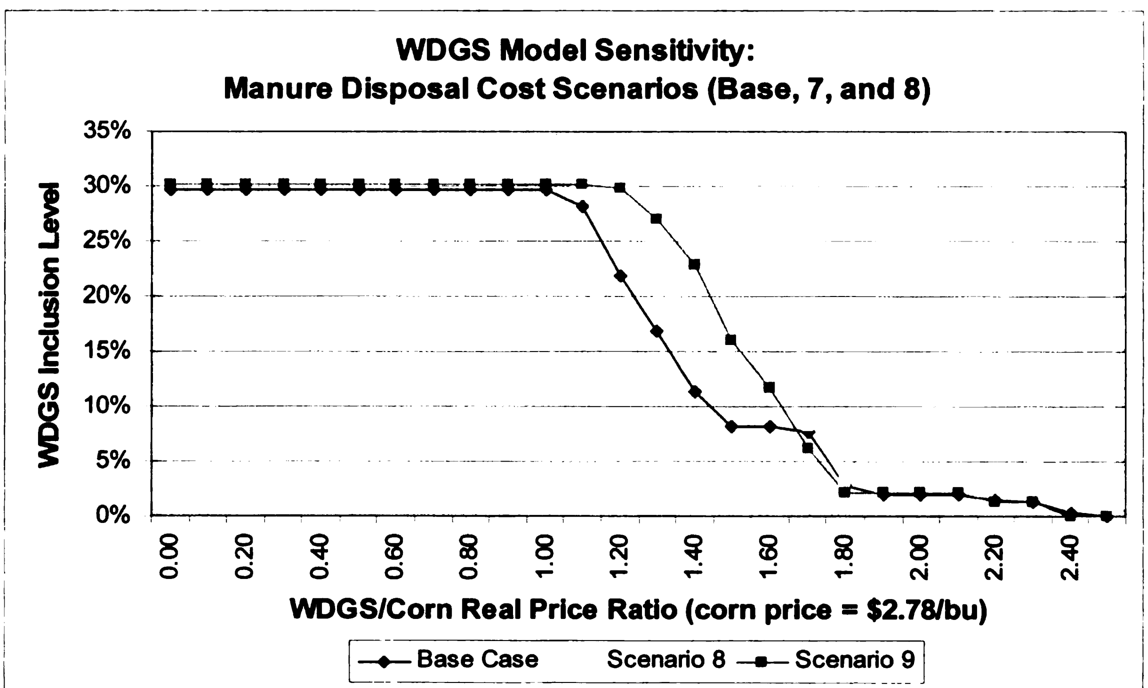
*Hash marks show range of historical DDGS/corn feed price ratios, based out of Chicago, IL (February 2006 – March 2007; LMIC).
**This assumes that all other parameters are held constant (e.g. output price, storage).

Figure Q1: DDGS Model Sensitivity: Manure Disposal Cost Scenarios 7 & 8



*Hash marks show range of historical DDGS/corn feed price ratios, based out of Chicago, IL (February 2006 – March 2007; LMIC).

Figure Q2: WDGS Model Sensitivity: Manure Disposal Cost Scenarios 7 & 8



*Hash marks show range of historical DDGS/corn feed price ratios, based out of Chicago, IL (February 2006 – March 2007; LMIC).

Figure R: Optimal DDGS Inclusion Levels under Various Animal Response Function Estimations (with Base Case Constraints Imposed)

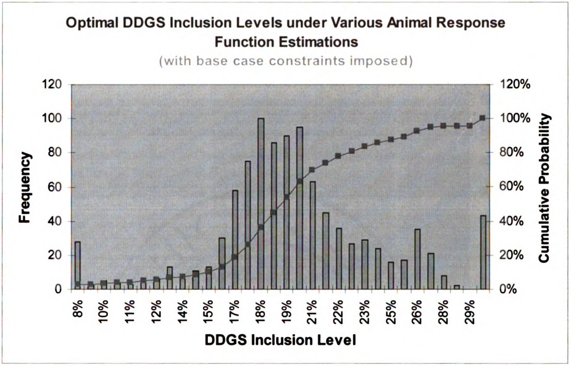


Figure S: Optimal DDGS Inclusion Levels under Various Animal Response Function Estimations (with Relaxed Fat and Calcium Constraints)

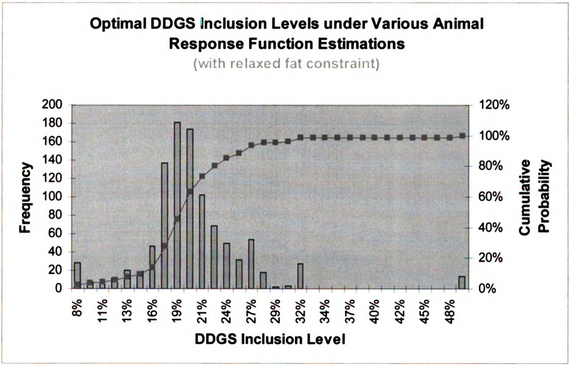
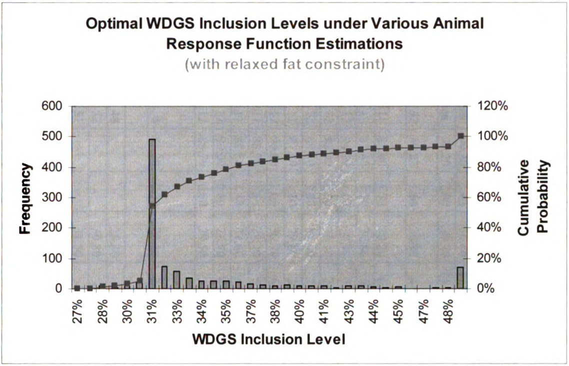


Figure T: Optimal WDGS Inclusion Levels under Various Animal Response Function Estimations (with Relaxed Fat and Calcium Constraints)



APPENDIX B: TABLES

Table 1: Nutrient Composition of DDGS [a]

Source	N	Dry Matter		Crude Protein		Fat		Fiber		Ash		ADF		NDF	
		%	CV	% DM	CV	% DM	CV	% DM	CV	% DM	CV	% DM	CV	% DM	CV
NRC, 1996 (Beef)	varies	90.30	2.43	30.40	11.68	10.70	29.16	6.90	19.28	4.60	18.70	21.30	22.63	46.00	18.93
NRC, 2001 (Dairy)	varies	90.20	2.00	29.70	11.11	10.00	34.00	-	-	5.20	21.15	19.70	23.35	38.80	20.10
University of Minnesota (2006)	32	89.22	1.66	30.92	4.86	10.84	16.01	7.20	17.18	6.00	25.60	13.81	23.08	-	-
Spiehs, et al. 2002: Total (1997-1999)	118	88.90	1.70	30.20	6.40	10.90	7.80	8.80	8.70	5.80	14.70	16.20	28.40	42.10	14.30
Plant 1	12	87.40	1.70	30.80	10.20	10.20	10.50	8.90	11.10	6.30	14.80	14.20	8.00	46.20	10.00
Plant 2	12	90.20	1.00	30.90	7.60	10.70	6.10	9.10	6.60	6.40	15.10	18.10	7.50	44.40	5.00
Plant 3	12	88.40	1.00	30.10	2.70	11.20	5.00	8.30	5.60	5.40	11.40	14.80	51.80	37.00	19.70
Plant 4	12	89.10	1.30	31.40	2.10	11.40	5.50	9.20	5.90	5.60	8.80	13.80	-	40.50	4.90
Plant 5	12	87.20	1.10	29.80	3.30	11.70	7.40	8.30	8.80	5.80	11.60	16.00	55.80	36.80	20.60
Plant 6	12	90.00	2.00	30.70	6.80	10.20	9.10	8.80	9.30	5.50	16.70	15.80	8.40	44.50	4.30
Plant 7	11	88.70	1.50	28.70	5.70	11.40	7.00	8.40	8.90	6.70	7.40	16.30	54.20	36.70	23.10
Plant 8	11	89.80	1.40	31.60	4.90	10.80	4.40	9.70	5.20	5.70	16.30	18.50	10.10	49.10	3.10
Plant 9	12	90.00	0.60	28.70	4.10	10.70	5.90	8.30	5.70	5.40	12.50	15.40	11.20	42.80	3.70
Plant 10	12	88.70	0.80	29.50	3.30	10.80	5.50	8.70	4.30	5.20	7.60	17.10	6.60	41.90	2.40
Spiehs, et al. 2002: Older Midwestern Plants	4	88.30	0.90	28.10	2.40	8.20	12.60	7.10	4.20	6.30	17.50	16.70	-	35.40	1.80
Belyea, et al. 2004															
1997	48	-	-	28.30	-	10.90	-	10.40	-	4.30	-	15.40	-	-	-
1998	52	-	-	30.80	-	11.90	-	10.60	-	5.00	-	16.30	-	-	-
1999	51	-	-	31.50	-	12.30	-	10.30	-	4.50	-	19.30	-	-	-
2000	48	-	-	32.90	-	12.40	-	9.60	-	4.50	-	15.70	-	-	-
2001	36	-	-	33.30	-	12.60	-	10.10	-	4.50	-	17.10	-	-	-

Table 1 (cont'd)

Source	N	Ca		P		K		Mg		S		Na	
		% DM	CV	% DM	CV	% DM	CV	% DM	CV	% DM	CV	% DM	CV
NRC, 1996 (Beef)	varies	0.26	88.46	0.83	18.07	1.08	25.00	0.33	24.24	0.44	27.27	0.30	86.67
NRC, 2001 (Dairy)	varies	0.22	45.45	0.83	16.87	1.10	20.91	0.33	21.21	0.44	34.09	0.30	90.00
University of Minnesota (2006)	32	0.06	47.54	0.77	18.46	1.01	21.28	0.30	22.92	0.68	47.88	0.18	67.84
Spiehs, et al. 2002: Total (1997-1999)	118	0.06	57.20	0.89	11.70	0.94	14.00	0.33	12.10	0.47	37.10	0.24	70.50
Plant 1	12	0.03	44.90	0.85	15.30	0.84	14.30	0.32	14.00	0.33	21.80	0.15	28.80
Plant 2	12	0.03	13.90	0.94	6.90	0.99	9.50	0.34	7.50	0.68	23.80	0.16	96.20
Plant 3	12	0.08	17.40	0.92	7.10	0.99	5.30	0.35	6.00	0.40	16.40	0.21	19.40
Plant 4	12	0.07	51.20	0.95	4.70	1.06	7.10	0.34	4.70	0.38	40.80	0.20	55.20
Plant 5	12	0.05	36.60	0.91	3.10	0.97	7.60	0.37	5.20	0.47	29.40	0.20	24.40
Plant 6	12	0.13	33.60	0.82	12.20	0.94	10.90	0.34	13.30	0.74	21.90	0.51	44.80
Plant 7	11	0.06	50.60	0.99	8.20	1.04	7.60	0.36	6.40	0.37	37.90	0.20	49.80
Plant 8	11	0.03	21.10	0.70	6.40	0.69	10.60	0.25	10.70	0.46	6.40	0.12	9.40
Plant 9	12	0.06	15.20	0.89	5.50	0.84	4.40	0.33	4.30	0.54	14.30	0.17	32.80
Plant 10	12	0.07	15.30	0.94	5.60	1.03	5.50	0.35	4.70	0.36	9.70	0.46	34.40
Spiehs, et al. 2002: Older Midwestern Plants	4	0.44	34.70	0.90	7.50	0.99	8.70	0.40	3.30	0.51	43.50	0.28	65.20

[a] Not all values were reported from every source.

Table 2: Meta-Analysis Data of Various Feeding Trials: Effect of Distiller's Grains on Yearling Performance

Trial	Author	State	Year	DGS* Type	% DGS in Ration	ADG (lbs/ day)	DMI (lbs DM/ day)	Feed/ Gain	Marbling Score**
1	Larson, et al.	Nebraska	1993	Control	0.00	3.61	25.21	0.00	.
1	Larson, et al.	Nebraska	1993	WDGS	5.20	3.76	24.64	5.20	.
1	Larson, et al.	Nebraska	1993	WDGS	12.60	3.85	24.05	12.60	.
1	Larson, et al.	Nebraska	1993	WDGS	40.00	3.85	21.30	40.00	.
2	Vander Pol, et al.	Nebraska	2004	Control	0.00	3.04	19.80	0.00	547
2	Vander Pol, et al.	Nebraska	2004	WDGS	20.00	3.04	20.00	20.00	536
2	Vander Pol, et al.	Nebraska	2004	WDGS	40.00	3.19	19.60	40.00	538
3	Vander Pol, et al.	Nebraska	2006a	Control	0.00	3.65	24.00	0.00	515
3	Vander Pol, et al.	Nebraska	2006a	WDGS	10.00	4.07	24.60	10.00	538
3	Vander Pol, et al.	Nebraska	2006a	WDGS	20.00	4.11	25.10	20.00	520
3	Vander Pol, et al.	Nebraska	2006a	WDGS	30.00	4.31	26.00	30.00	523
3	Vander Pol, et al.	Nebraska	2006a	WDGS	40.00	4.27	24.40	40.00	501
3	Vander Pol, et al.	Nebraska	2006a	WDGS	50.00	3.92	23.30	50.00	505
4	Loza, et al.	Nebraska	2005	Control	0.00	3.99	24.30	0.00	.
4	Loza, et al.	Nebraska	2005	WDGS & CGF	12.50	4.63	26.40	12.50	.
4	Loza, et al.	Nebraska	2005	WDGS & CGF	25.00	4.56	25.80	25.00	.
4	Loza, et al.	Nebraska	2005	WDGS & CGF	37.50	3.90	23.30	37.50	.
5	Buckner, et al.	Nebraska	2007a	Control	0.00	4.06	23.70	0.00	481
5	Buckner, et al.	Nebraska	2007a	WDGS	30.00	4.67	25.00	30.00	487
6	Bremer, et al.	Nebraska	2006	Control	0.00	3.76	25.10	0.00	567
6	Bremer, et al.	Nebraska	2006	DDGS	30.00	4.01	26.30	30.00	544
7	Cole, et al.	Texas	2006	Control	0.00	3.32	18.60	0.00	.
7	Cole, et al.	Texas	2006	DDGS	10.00	3.08	17.50	10.00	.
8	Vander Pol, et al.	Nebraska	2004	Control	0.00	4.94	27.00	0.00	.
8	Vander Pol, et al.	Nebraska	2004	DDGS	20.00	4.94	27.10	20.00	.
8	Vander Pol, et al.	Nebraska	2004	DDGS	40.00	5.08	27.00	40.00	.
9	Benson, et al.	S. Dakota	2005	Control	0.00	4.25	23.74	0.00	537
9	Benson, et al.	S. Dakota	2005	DDGS	15.00	4.39	24.13	15.00	518
9	Benson, et al.	S. Dakota	2005	DDGS	25.00	4.55	24.81	25.00	530
9	Benson, et al.	S. Dakota	2005	DDGS	35.00	4.45	24.06	35.00	510

*CGF = Corn Gluten Feed

** Marbling scores were not reported for all feeding trials.

***Vander Pol, et al. (2004) reported two separate feeding trials within one document.

Table 2 (cont'd)

Trial	Author	State	Year	DGS Type	% DGS in Ration	ADG (lbs/ day)	DMI (lbs DM/ day)	Feed/ Gain	Marbling Score**
10	Gordon, et al.	Kansas	2002	Control	0.00	2.19	16.40	7.49	618
10	Gordon, et al.	Kansas	2002	DDGS	15.00	2.37	17.00	7.17	669
10	Gordon, et al.	Kansas	2002	DDGS	30.00	2.21	16.70	7.56	623
10	Gordon, et al.	Kansas	2002	DDGS	45.00	2.10	16.50	7.86	678
10	Gordon, et al.	Kansas	2002	DDGS	60.00	2.05	16.40	8.00	621
10	Gordon, et al.	Kansas	2002	DDGS	75.00	1.85	15.50	8.38	552
11	Buckner, et al.	Nebraska	2007b	Control	0.00	3.29	20.80	6.32	540
11	Buckner, et al.	Nebraska	2007b	DDGS	10.00	3.55	21.80	6.14	548
11	Buckner, et al.	Nebraska	2007b	DDGS	20.00	3.71	20.80	5.61	550
11	Buckner, et al.	Nebraska	2007b	DDGS	30.00	3.56	21.20	5.96	533
11	Buckner, et al.	Nebraska	2007b	DDGS	40.00	3.56	20.70	5.81	522
12	Fanning, et al.	Nebraska	1999	Control	0.00	3.64	23.50	6.46	558
12	Fanning, et al.	Nebraska	1999	DDGS	30.00	3.95	22.90	5.80	544
13	Ham, et al.	Nebraska	1994a	Control	0.00	3.23	24.22	7.50	.
13	Ham, et al.	Nebraska	1994a	WDGS	40.00	3.71	23.53	6.34	.
13	Ham, et al.	Nebraska	1994a	DDGS	40.00	3.71	25.40	6.85	.
14	Lodge, et al.	Nebraska	1995	Control	0.00	4.10	26.70	6.51	.
14	Lodge, et al.	Nebraska	1995	WDGS	40.00	4.22	26.96	6.39	.
14	Lodge, et al.	Nebraska	1995	DDGS	40.00	3.93	27.53	7.01	.
14	Lodge, et al.	Nebraska	1995	WDG	0.00	3.18	20.60	6.53	.
15	Cole, et al.	Kansas	2006	Control	15.00	3.11	20.30	6.48	.
15	Cole, et al.	Kansas	2006	WDGS	15.00	3.19	20.90	6.53	.
15	Cole, et al.	Kansas	2006	DDGS	0.00	3.63	21.82	6.55	.
16	Mateo et al.	S. Dakota	2004	Control	20.00	3.72	22.37	6.01	528
16	Mateo et al.	S. Dakota	2004	WDGS	40.00	3.74	20.82	6.01	557
16	Mateo et al.	S. Dakota	2004	WDGS	20.00	3.65	23.15	5.57	520
16	Mateo et al.	S. Dakota	2004	DDGS	40.00	3.72	23.42	6.34	544
16	Mateo et al.	S. Dakota	2004	DDGS	0.00	3.50	19.60	6.30	528
17	Trenkle	Iowa	1996	Control	16.00	3.80	20.30	5.61	.
17	Trenkle	Iowa	1996	WDGS	28.00	3.64	19.00	5.34	.
17	Trenkle	Iowa	1996	WDGS	40.00	3.59	18.40	5.22	.
17	Trenkle	Iowa	1996	WDGS	16.00	3.72	21.00	5.13	.
17	Trenkle	Iowa	1996	DDGS	0.00	2.19	16.40	5.65	.

** Marbling scores were not reported for all feeding trials.

Table 3a: Phosphorus Excretion Levels at Various DDGS Inclusion Levels

Trial #	Author	State	Year	DGS Type	% DGS Inclusion	Phosphorus Excreted, ppm
9	Benson, et al.	S. Dakota	2005	Control	0.0	710
9	Benson, et al.	S. Dakota	2005	DDGS	15.0	860
9	Benson, et al.	S. Dakota	2005	DDGS	25.0	1013
9	Benson, et al.	S. Dakota	2005	DDGS	35.0	1163

Table 3b: Phosphorus Excretion Levels at Various WDGS Inclusion Levels

Feed Ingredient*	Percent Dry Matter		
WDGS	0.0	10.0	20.0
Corn	86.2	77.1	67.7
Corn Silage	5.0	5.0	5.0
Hay	5.0	5.0	5.0
Urea	1.3	0.5	0.0
Nutrient Composition	**Percent Dry Matter**		
Crude Protein	12.05	12.26	13.14
Phosphorus	0.29	0.33	0.38
Nutrient Excreted	**Grams/Steer/Day**		
Phosphorus	13.2	17.3	19

Source: Meyer, et al. 2006

*Additional feed ingredients can be found within above cited report.

Table 3c: Phosphorus and NitrogenExcretion Levels at Various DDGS Inclusion Levels

Feed Ingredient	Percent Dry Matter			
DDGS	0.0	15.0	25.0	40.0
Hay	10.0	10.0	10.0	10.0
Corn	81.5	72.9	62.7	47.5
Protein Supplement	8.5	0.0	0.0	0.0
Calcium Supplement	0.0	2.1	2.3	2.5
Nutrient Composition	**Percent Dry Matter**			
Crude Protein	12.58	12.56	14.64	17.78
Phosphorus	0.35	0.42	0.47	0.55
Nutrient Excreted	**Pounds per Finished Animal**			
Nitrogen	60	60	72	89
Phosphorus	10	12	14	17

Source: Powers, et al. 2006

Table 4: Base Case Model Parameters

Profit Function Component	Parameter	Unit	Base Case
ANIMAL RESPONSE FUNCTIONS	Average Daily Gain Equation		
	Constant	Coefficient	3.6106
	X_{DDGS}	Coefficient	0.0160
	X^2_{DDGS}	Coefficient	-0.0003
	X_{WDGS}	Coefficient	0.0244
	X^2_{WDGS}	Coefficient	-0.0005
	Dry Matter Intake Equation		
	Constant	Coefficient	22.6524
	X_{DDGS}	Coefficient	0.0559
	X^2_{DDGS}	Coefficient	-0.0011
	X_{WDGS}	Coefficient	0.0574
	X^2_{WDGS}	Coefficient	-0.0020
REVENUE	Output price	$/cwt	100
	Finished weight	lbs	1250
FEED COSTS	Feed Prices		
	DDGS	$/ton	101.53
	WDGS	$/ton	31.14
	Corn, Dry	$/bu.	2.78
	Corn Silage	$/ton	26.46
	Soybean Meal	$/ton	181.00
	Hay	$/ton	106.29
	Urea	$/ton	361.50
	Limestone	$/ton	80.00
	Transport and Additional Handling Costs		
	DGS Transport	miles	0
	Transport cost	$/loaded mile	2.5
	Load	ton	25
	WDGS (additional handling/storage)	$/lb DM	0
NUTRIENT AND FEED INGREDIENT CONSTRAINTS	Nutritional Constraints		
	Minimum Calcium	% DM	0.40
	Minimum Phosphorus	% DM	0.30
	Minimum Calcium : Phosphorus	Ratio	1.20
	Minimum Effective Fiber	% DM	8.00
	Minimum Crude Protein	% DM	12.00
	Maximum Fat	% DM	6.00
	Maximum Sulfur	% DM	0.40
	Feed Ingredient Constraints		
	Maximum Distiller's Grains	% DM	50.00
	Maximum Roughage (Hay & Corn Silage)	% DM	12.00
	Minimum Roughage (Hay & Corn Silage)	% DM	8.00
	Maximum Urea	% DM	1.00
	Minimum Urea	% DM	0.30
	Maximum Limestone	% DM	2.00

Table 4 (cont'd)

Profit Function Component	Parameter	Unit	Base Case
OTHER VARIABLE COSTS	Yardage Costs	\$/day/head	0.33
	Interest Rate	%/yr	8
	Cost of Feeder Steer	\$/cwt	93.49
	Starting Weight	lbs	775
MANURE DISPOSAL COSTS	MDC taken into Account?	Yes/No	yes
	Size of Operation	# Head	1,000
	Land Accessible for Disposal	acres/mile	500
	Corn	%	45
	Soybean	%	45
	Corn Silage	%	10
	Application Rate Scenario	A/B	A
	Hourly Cost of Disposal	\$/hr	150
	Tank Size	gal	6,000
	Loading Time	min/load	12.11
	Unloading Time	min/acre	6.19
	Incorporation Time	min/acre	2.75
	Travel Speed to Field	mph	14
	Travel Speed on Return	mph	17
	Value of P_2O_5	\$/lb	0
	Value of Nitrogen	\$/lb	0

Table 5: Nutrient Composition Values

	Feed Ingredient							
	WDGS[a]	DDGS[a]	Corn,[b] Dry	Corn[b] Silage	Soybean[b] Meal	Hay[b,c]	Urea[b]	Lime-stone[b]
Dry Matter, %	30.0	90.0	88.0	34.6	89.1	89.3	99.0	100.0
Nutrient	Percent Dry Matter							
Calcium	0.06	0.06	0.03	0.25	0.40	0.83	0.00	34.00
Phosphorus	0.77	0.77	0.31	0.22	0.71	0.25	0.00	0.02
Fat	10.84	10.84	4.30	3.09	1.60	2.40	0.00	0.00
Sulfur	0.68	0.68	0.14	0.12	0.46	0.14	0.00	0.04
Crude Protein	30.92	30.92	9.80	8.65	49.90	16.55	281.00	0.00
Effective Fiber[b]	1.84	1.84	5.40	37.26	3.43	49.81	0.00	0.00

Source: [a] University of Minnesota 2006; [b] NRC, *Nutrient Requirements of Beef,* 1996
[c] Hay values were calculated using a mix of 50% alfalfa and 50% brome hay.

Table 6: Nutrient Removal Rates

Crop	Unit	Potential Yield	P2O5* Removal Rate	Nitrogen* Removal Rate	Nitrogen* Credits	P205 Removal Rate	Nitrogen Removal Rate
		units/acre	lbs/unit	lbs/unit	lbs/acre	lbs/acre	lbs/acre
Corn	bu.	150	0.37	0.90	0	55.50	135.00
Soybean	bu.	45	0.80	3.80	30	36.00	141.00
Corn Silage	ton	22	3.30	9.40	0	72.60	206.80

* Source: Warncke, et al. 2004

Table 7a: Estimated Nutrient Excretion Levels at Various DDGS Inclusion Levels

Feed Ingredient	Percent Dry Matter				
DDGS	0.0	10.0	20.0	30.0	40.0
Corn, Dry	84.9	75.7	65.7	55.7	45.7
Corn Silage	12.0	12.0	12.0	12.0	9.4
Hay	0.0	0.0	0.0	0.0	2.6
Urea	0.7	0.3	0.3	0.3	0.3
Limestone	1.0	2.0	2.0	2.0	2.0
Nutrient Composition	**Percent Dry Matter**				
Crude Protein	12.0	12.4	14.5	16.6	18.9
Phosphorus	0.3	0.3	0.4	0.4	0.5
Nutrient Excreted	**Pounds per Finished Animal**				
Nitrogen	48.8	49.8	59.3	69.2	80.7
Phosphorus	6.7	7.7	9.0	10.4	11.8
Days on Feed	**Number**				
Days on Feed	131	127	125	125	127

Table 7b: Estimated Nutrient Excretion Levels at Various WDGS Inclusion Levels

Feed Ingredient	Percent Dry Matter				
WDGS	0.0	10.0	20.0	30.0	40.0
Corn, Dry	84.9	75.7	65.7	55.7	45.7
Corn Silage	12.0	12.0	12.0	12.0	9.4
Hay	0.0	0.0	0.0	0.0	2.6
Urea	0.7	0.3	0.3	0.3	0.3
Limestone	1.0	2.0	2.0	2.0	2.0
Nutrient Composition	**Percent Dry Matter**				
Crude Protein	12.0	12.4	14.5	16.6	18.9
Phosphorus	0.3	0.3	0.4	0.4	0.5
Nutrient Excreted	**Pounds per Finished Animal**				
Nitrogen	48.8	48.6	56.6	64.5	73.4
Phosphorus	6.7	7.5	8.6	9.6	10.7
Days on Feed	**Number**				
Days on Feed	131	124	121	121	124

Table 8a: Base Case DDGS Model Results

Base Case DDGS Model Results					
Feed Ingredient	Price/Unit	Unit	DM	$/lb DM	Inclusion in Diet
DDGS	$ 101.53	ton	90%	0.056	18.4%
Corn, Dry	$ 2.78	bu.	88%	0.056	67.3%
Corn Silage	$ 26.46	ton	35%	0.038	12.0%
Soybean Meal	$ 182.63	ton	90%	0.102	0.0%
Hay	$ 106.29	ton	89%	0.060	0.0%
Urea	$ 361.50	ton	99%	0.183	0.3%
Limestone	$ 80.00	ton	100%	0.040	2.0%

Table 8b: Base Case WDGS Model Results

Base Case WDGS Model Results					
Feed Ingredient	Price/Unit	Unit	DM	$/lb DM	Inclusion in Diet
WDGS	$ 31.14	ton	30%	0.052	29.7%
Corn, Dry	$ 2.78	bu.	88%	0.056	56.0%
Corn Silage	$ 26.46	ton	35%	0.038	12.0%
Soybean Meal	$ 182.63	ton	90%	0.102	0.0%
Hay	$ 106.29	ton	89%	0.060	0.0%
Urea	$ 361.50	ton	99%	0.183	0.3%
Limestone	$ 80.00	ton	100%	0.040	2.0%

Table 9: Base Model Shadow Values for Nutrient and Feed Ingredient Constraints

Base Model Nutrient and Feed Ingredient Constraints			Shadow Value*	
Nutritional Constraints			DDGS Model	WDGS Model
Crude Protein	>=	12.00%	0.0	0.0
Calcium (Ca)	>=	0.40%	0.0	0.0
Phosphorus (P)	>=	0.30%	0.0	0.0
Ca : P	>=	1.20	0.0	0.0
Effective Fiber	>=	8.00%	0.0	0.0
Fat	<=	6.00%	0.0	350.5
Sulfur	<=	0.40%	0.0	0.0
Feed Ingredient Constraints			DDGS Model	WDGS Model
Distiller's Grains	<=	50.00%	0.0	0.0
Roughage	<=	12.00%	55.9	56.6
Roughage	>=	8.00%	0.0	0.0
Urea	<=	1.00%	0.0	0.0
Urea	>=	0.30%	482.0	426.3
Limestone	<=	2.00%	57.4	68.2

*Due to the non-linearity of the model, caution is advised when interpreting these shadow values.

Table 10a: Optimal DDGS Inclusion Levels and Constraint Shadow Values across DDGS/Corn Price Scenarios

	DDGS/Corn Price Ratio (Corn = $2.78/bu or $0.056/lb DM)												
DDGS Model	**0.00**	**0.20**	**0.40**	**0.60**	**0.80**	**1.00**	**1.20**	**1.40**	**1.60**	**1.80**	**2.00**	**2.20**	**2.40**
Feed Ingredient	**Inclusion Levels**												
DDGS	**29.7%**	**29.7%**	**29.7%**	**29.7%**	**29.7%**	**18.4%**	**8.2%**	**7.9%**	**2.0%**	**2.0%**	**1.4%**	0.0%	0.0%
Corn, Dry	**56.0%**	**56.0%**	**56.0%**	**56.0%**	**56.0%**	**67.3%**	**77.6%**	**77.8%**	**83.3%**	**83.3%**	**84.9%**	**84.9%**	**84.9%**
Corn Silage	**12.0%**	**12.0%**	**12.0%**	**12.0%**	**12.0%**	**12.0%**	**12.0%**	**12.0%**	**12.0%**	**12.0%**	**12.0%**	**12.0%**	**12.0%**
Soybean Meal	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	**1.5%**	**1.5%**
Hay	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Urea	**0.3%**	**0.3%**	**0.3%**	**0.3%**	**0.3%**	**0.3%**	**0.3%**	**0.3%**	**0.8%**	**0.8%**	**0.8%**	**0.7%**	**0.7%**
Limestone	**2.0%**	**2.0%**	**2.0%**	**2.0%**	**2.0%**	**2.0%**	**2.0%**	**2.0%**	**2.0%**	**2.0%**	**1.0%**	**1.0%**	**1.0%**
Constraint	**Shadow Values***												
Crude Protein	0.0	0.0	0.0	0.0	0.0	0.0	**24.4**	**179.4**	**180.2**	**188.3**	**196.1**	**198.5**	**198.5**
Calcium (Ca)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	**38.4**	**53.9**	**53.9**
Phosphorus (P)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	**3,652.3**	**10,689.9**	**17,382.0**	**19,175.6**	**19,175.6**
Ca:P Ratio	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Effective Fiber	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Fat	**2,122.9**	**1,604.8**	**1,086.7**	**568.6**	**50.5**	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Sulfur	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Max Distiller's Grains	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Max Roughage	**81.9**	**75.7**	**69.4**	**63.1**	**56.9**	**55.9**	**55.7**	**53.9**	**51.1**	**44.7**	**38.7**	**37.3**	**37.3**
Min Roughage	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Max Urea	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Min Urea	**412.7**	**435.0**	**457.3**	**479.6**	**501.8**	**482.0**	**420.7**	0.0	0.0	0.0	0.0	0.0	0.0
Max Limestone	**150.3**	**128.1**	**105.8**	**83.5**	**61.2**	**57.4**	**54.0**	**38.9**	**28.3**	**7.1**	0.0	0.0	0.0

*Due to the non-linearity of the model, caution is advised when interpreting these shadow values.

Table 10b: Optimal WDGS Inclusion Levels and Constraint Shadow Values across WDGS/Corn Price Scenarios

	WDGS/Corn Price Ratio (Corn = $2.78/bu or $0.056/lb DM)												
WDGS Model	**0.00**	**0.20**	**0.40**	**0.60**	**0.80**	**1.00**	**1.20**	**1.40**	**1.60**	**1.80**	**2.00**	**2.20**	**2.40**
Feed Ingredient	**Inclusion Levels**												
WDGS	**29.7%**	**29.7%**	**29.7%**	**29.7%**	**29.7%**	**29.7%**	**21.8%**	**11.3%**	**8.2%**	**2.8%**	**2.0%**	**1.6%**	**0.4%**
Corn, Dry	**56.0%**	**56.0%**	**56.0%**	**56.0%**	**56.0%**	**56.0%**	**63.9%**	**74.4%**	**77.6%**	**82.5%**	**83.3%**	**84.3%**	**84.9%**
Corn Silage	**12.0%**	**12.0%**	**12.0%**	**12.0%**	**12.0%**	**12.0%**	**12.0%**	**12.0%**	**12.0%**	**12.0%**	**12.0%**	**12.0%**	**12.0%**
Soybean Meal	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	**1.1%**
Hay	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Urea	**0.3%**	**0.3%**	**0.3%**	**0.3%**	**0.3%**	**0.3%**	**0.3%**	**0.3%**	**0.3%**	**0.7%**	**0.8%**	**0.8%**	**0.7%**
Limestone	**2.0%**	**2.0%**	**2.0%**	**2.0%**	**2.0%**	**2.0%**	**2.0%**	**2.0%**	**2.0%**	**2.0%**	**2.0%**	**1.3%**	**1.0%**
Constraint	**Shadow Values***												
Crude Protein	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	**107.5**	**175.6**	**182.7**	**190.5**	**198.3**
Calcium (Ca)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	**53.8**
Phosphorus (P)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	**6,318.6**	**12,997.0**	**19,144.2**
Ca:P Ratio	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Effective Fiber	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Fat	**2,446.9**	**1,991.2**	**1,535.4**	**1,079.7**	**623.9**	**168.2**	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Sulfur	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Max Distiller's Grains	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Max Roughage	**82.0**	**76.4**	**70.9**	**65.4**	**59.9**	**54.4**	**53.3**	**54.5**	**53.7**	**54.0**	**48.5**	**42.4**	**37.2**
Min Roughage	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Max Urea	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Min Urea	**336.2**	**355.8**	**375.4**	**395.0**	**414.6**	**434.2**	**457.5**	**469.0**	**188.9**	0.0	0.0	0.0	0.0
Max Limestone	**158.4**	**138.8**	**119.2**	**99.6**	**80.0**	**60.4**	**54.6**	**54.9**	**44.9**	**38.9**	**20.0**	0.0	0.0

*Due to the non-linearity of the model, caution is advised when interpreting these shadow values.

Table 11a: DDGS Model: Sensitivity Analysis to Binding Nutrient and Feed Ingredient Constraints

DDGS Model Scenario	DDGS/ Corn Price Ratio	Change in Profit ($/head)	Ration Dry Matter					Shadow Value*							
			DDGS	Corn, Dry	Roug-hage	Urea	Lime-stone	Crude Protein	Calcium	Effective Fiber	Fat	Sulfur	Max Roug-hage	Min Urea	Max Lime-stone
Base Case	0.78	-	29.7%	56.0%	12.0%	0.3%	2.0%	0.0	0.0	0.0	**102.3**	0.0	**57.5**	**499.6**	**63.5**
	1.00	-	18.4%	67.3%	12.0%	0.3%	2.0%	0.0	0.0	0.0	0.0	0.0	**55.9**	**482.0**	**57.4**
	1.24	-	8.2%	77.6%	12.0%	0.3%	2.0%	**56.2**	0.0	0.0	0.0	0.0	**55.3**	**334.7**	**50.9**
Fat<=7.5%	0.78	0.06	30.9%	54.8%	12.0%	0.3%	2.0%	0.0	0.0	**114.9**	0.0	0.0	**92.8**	**511.1**	**52.8**
	1.00	0.00	18.4%	67.3%	12.0%	0.3%	2.0%	0.0	0.0	0.0	0.0	0.0	**55.9**	**482.0**	**57.4**
	1.24	0.00	8.2%	77.6%	12.0%	0.3%	2.0%	**56.2**	0.0	0.0	0.0	0.0	**55.3**	**334.7**	**50.9**
Fat<=4.5%	0.78	-9.20	6.9%	78.7%	12.0%	0.4%	2.0%	**154.1**	0.0	0.0	**1554.0**	0.0	**73.1**	0.0	**108.2**
	1.00	-2.41	6.9%	78.7%	12.0%	0.4%	2.0%	**162.7**	0.0	0.0	**1016.5**	0.0	**66.5**	0.0	**84.2**
	1.24	-0.36	6.9%	78.7%	12.0%	0.4%	2.0%	**172.0**	0.0	0.0	**430.2**	0.0	**59.3**	0.0	**58.1**
Sulfur <=0.30%	0.78	0.00	29.7%	56.0%	12.0%	0.3%	2.0%	0.0	0.0	0.0	**102.3**	0.0	**57.5**	**499.6**	**63.5**
	1.00	0.00	18.4%	67.3%	12.0%	0.3%	2.0%	0.0	0.0	0.0	0.0	0.0	**55.9**	**482.0**	**57.4**
	1.24	0.00	8.2%	77.6%	12.0%	0.3%	2.0%	**56.2**	0.0	0.0	0.0	0.0	**55.3**	**334.7**	**50.9**
Sulfur <=0.30%; Fat <=7.5%	0.78	0.05	30.5%	55.2%	12.0%	0.3%	2.0%	0.0	0.0	0.0	0.0	**904.2**	**56.4**	**503.3**	**59.9**
	1.00	0.00	18.4%	67.3%	12.0%	0.3%	2.0%	0.0	0.0	0.0	0.0	0.0	**55.9**	**482.0**	**57.4**
	1.24	0.00	8.2%	77.6%	12.0%	0.3%	2.0%	**56.2**	0.0	0.0	0.0	0.0	**55.3**	**334.7**	**50.9**
Crude Protein >= 15%; Fat <=4.5%	0.78	-15.02	8.3%	74.0%	12.0%	1.0%	2.0%	**253.8**	0.0	0.0	**1845.3**	0.0	**75.5**	0.0	**110.4**
	1.00	-8.77	8.3%	74.0%	12.0%	1.0%	2.0%	**285.0**	0.0	0.0	**1382.6**	0.0	**69.6**	0.0	**87.5**
	1.24	-7.32	8.3%	74.0%	12.0%	1.0%	2.0%	**318.9**	0.0	0.0	**877.9**	0.0	**63.1**	0.0	**62.5**
Crude Protein >= 9%; Fat <=4.5%	0.78	-8.76	6.8%	78.9%	12.0%	0.3%	2.0%	0.0	0.0	0.0	**1054.0**	0.0	**68.8**	**446.1**	**101.9**
	1.00	-1.94	6.8%	78.9%	12.0%	0.3%	2.0%	0.0	0.0	0.0	**488.9**	0.0	**62.0**	**470.4**	**77.6**
	1.24	0.27	3.7%	82.0%	12.0%	0.3%	2.0%	0.0	0.0	0.0	0.0	0.0	**56.3**	**503.0**	**56.8**

*Due to the non-linearity of the model, caution is advised when interpreting these shadow values.

Table 11a (cont'd)

DDGS Model Scenario	DDGS/ Corn Price Ratio	Change in Profit ($/head)	Ration Dry Matter					Shadow Value*							
			DDGS	Corn, Dry	Roug-hage	Urea	Lime-stone	Crude Protein	Calcium	Effective Fiber	Fat	Sulfur	Max Roug-hage	Min Urea	Max Lime-stone
Base Case	0.78	-	29.7%	56.0%	12.0%	0.3%	2.0%	0.0	0.0	0.0	**102.3**	0.0	**57.5**	**499.6**	**63.5**
	1.00	-	18.4%	67.3%	12.0%	0.3%	2.0%	0.0	0.0	0.0	0.0	0.0	**55.9**	**482.0**	**57.4**
	1.24	-	8.2%	77.6%	12.0%	0.3%	2.0%	**56.2**	0.0	0.0	0.0	0.0	**55.3**	**334.7**	**50.9**
Without Urea Minimum	0.78	1.50	29.5%	56.5%	12.0%	0.0%	2.0%	0.0	0.0	0.0	**112.0**	0.0	**57.5**	0.0	**63.8**
	1.00	1.45	19.2%	66.8%	12.0%	0.0%	2.0%	0.0	0.0	0.0	0.0	0.0	**55.5**	0.0	**56.1**
	1.24	0.81	12.0%	74.0%	12.0%	0.0%	2.0%	**106.5**	0.0	0.0	0.0	0.0	**54.5**	0.0	**46.0**
Maximum Roughage <=15%	0.78	1.72	30.3%	52.4%	15.0%	0.3%	2.0%	0.0	0.0	0.0	**83.0**	0.0	**57.3**	**500.2**	**62.6**
	1.00	1.68	18.4%	64.3%	15.0%	0.3%	2.0%	0.0	0.0	0.0	0.0	0.0	**55.9**	**481.6**	**57.4**
	1.24	1.66	8.3%	74.4%	15.0%	0.3%	2.0%	**58.9**	0.0	0.0	0.0	0.0	0.0	**326.2**	**50.6**
Maximum Roughage <=9%	0.78	-6.27	24.4%	64.3%	9.0%	0.3%	2.0%	0.0	0.0	**537.6**	0.0	0.0	**227.8**	**528.7**	**30.6**
	1.00	-3.82	11.9%	76.8%	9.0%	0.3%	2.0%	0.0	0.0	**532.7**	0.0	0.0	**225.5**	**502.0**	**27.4**
	1.24	-2.31	7.6%	81.1%	9.0%	0.3%	2.0%	**125.3**	0.0	**458.8**	0.0	0.0	**200.8**	**172.4**	**19.4**
Maximum Limestone <=2.5%	0.78	0.32	30.1%	55.1%	12.0%	0.3%	2.5%	0.0	0.0	0.0	**90.5**	0.0	**57.4**	**500.1**	**63.0**
	1.00	0.29	18.4%	66.8%	12.0%	0.3%	2.5%	0.0	0.0	0.0	0.0	0.0	**55.9**	**482.0**	**57.4**
	1.24	0.25	8.4%	76.8%	12.0%	0.3%	2.5%	**59.2**	0.0	0.0	0.0	0.0	**55.3**	**326.3**	**50.6**
Maximum Limestone <=1.5%	0.78	-0.32	29.4%	56.8%	12.0%	0.3%	1.5%	0.0	0.0	0.0	**114.0**	0.0	**57.6**	**499.1**	**63.9**
	1.00	-0.29	18.5%	67.7%	12.0%	0.3%	1.5%	0.0	0.0	0.0	0.0	0.0	**55.9**	**482.0**	**57.3**
	1.24	-0.26	7.9%	78.3%	12.0%	0.3%	1.5%	**53.2**	0.0	0.0	0.0	0.0	**55.4**	**343.1**	**51.2**

*Due to the non-linearity of the model, caution is advised when interpreting these shadow values.

Table 11b: WDGS Model: Sensitivity Analysis to Binding Nutrient and Feed Ingredient Constraints

WDGS Model Scenario	WDGS/ Corn Price Ratio	Change in Profit ($/head)	Ration Dry Matter					Shadow Value*							
			WDGS	Corn, Dry	Roug-hage	Urea	Lime-stone	Crude Protein	Calcium	Effective Fiber	Fat	Sulfur	Max Roug-hage	Min Urea	Max Lime-stone
Base Case	0.74	-	29.7%	56.0%	12.0%	0.3%	2.0%	0.0	0.0	0.0	**760.7**	0.0	**61.6**	**408.7**	**85.9**
	0.92	-	29.7%	56.0%	12.0%	0.3%	2.0%	0.0	0.0	0.0	**350.5**	0.0	**56.6**	**426.3**	**68.2**
	1.01	-	29.7%	56.0%	12.0%	0.3%	2.0%	0.0	0.0	0.0	**145.4**	0.0	**54.1**	**435.1**	**59.4**
Fat<=7.5%	0.74	1.84	40.9%	44.8%	12.0%	0.3%	2.0%	0.0	0.0	**497.9**	0.0	0.0	**210.5**	**491.5**	**27.4**
	0.92	0.26	31.5%	54.2%	12.0%	0.3%	2.0%	0.0	0.0	**497.9**	0.0	0.0	**210.5**	**478.9**	**25.6**
	1.01	0.09	30.9%	54.8%	12.0%	0.3%	2.0%	0.0	0.0	**189.8**	0.0	0.0	**112.7**	**448.9**	**42.7**
Fat<=4.5%	0.74	-19.41	6.9%	78.7%	12.0%	0.4%	2.0%	**140.1**	0.0	0.0	**2315.5**	0.0	**81.6**	0.0	**141.4**
	0.92	-13.05	6.9%	78.7%	12.0%	0.4%	2.0%	**146.8**	0.0	0.0	**1888.7**	0.0	**76.4**	0.0	**122.4**
	1.01	-9.87	6.9%	78.7%	12.0%	0.4%	2.0%	**150.2**	0.0	0.0	**1675.3**	0.0	**73.8**	0.0	**112.9**
Sulfur <=0.30%	0.74	0.00	29.7%	56.0%	12.0%	0.3%	2.0%	0.0	0.0	0.0	**760.7**	0.0	**61.6**	**408.7**	**85.9**
	0.92	0.00	29.7%	56.0%	12.0%	0.3%	2.0%	0.0	0.0	0.0	**350.5**	0.0	**56.6**	**426.3**	**68.2**
	1.01	0.00	29.7%	56.0%	12.0%	0.3%	2.0%	0.0	0.0	0.0	**145.4**	0.0	**54.1**	**435.1**	**59.4**
Sulfur <=0.30%; Fat <=7.5%	0.74	0.39	30.5%	55.2%	12.0%	0.3%	2.0%	0.0	0.0	0.0	0.0	**8847.5**	**54.0**	**427.1**	**61.9**
	0.92	0.17	30.5%	55.2%	12.0%	0.3%	2.0%	0.0	0.0	0.0	0.0	**3886.8**	**53.0**	**434.0**	**56.9**
	1.01	0.07	30.5%	55.2%	12.0%	0.3%	2.0%	0.0	0.0	0.0	0.0	**1406.5**	**52.6**	**437.5**	**54.5**
Crude Protein >= 15%; Fat <=4.5%	0.74	-24.34	8.3%	74.0%	12.0%	1.0%	2.0%	**204.2**	0.0	0.0	**2483.9**	0.0	**82.8**	0.0	**141.7**
	0.92	-18.42	8.3%	74.0%	12.0%	1.0%	2.0%	**228.8**	0.0	0.0	**2118.8**	0.0	**78.1**	0.0	**123.6**
	1.01	-15.45	8.3%	74.0%	12.0%	1.0%	2.0%	**241.0**	0.0	0.0	**1936.2**	0.0	**75.8**	0.0	**114.6**
Crude Protein >= 9%; Fat <=4.5%	0.74	-19.00	6.8%	78.9%	12.0%	0.3%	2.0%	0.0	0.0	0.0	**1861.1**	0.0	**77.7**	**406.0**	**135.7**
	0.92	-12.62	6.8%	78.9%	12.0%	0.3%	2.0%	0.0	0.0	0.0	**1412.3**	0.0	**72.3**	**425.3**	**116.4**
	1.01	-9.43	6.8%	78.9%	12.0%	0.3%	2.0%	0.0	0.0	0.0	**1187.8**	0.0	**69.6**	**435.0**	**106.8**

*Due to the non-linearity of the model, caution is advised when interpreting these shadow values.

Table 11b (cont'd)

WDGS Model Scenario	WDGS/ Corn Price Ratio	Change in Profit ($/head)	Ration Dry Matter					Shadow Value*							
			WDGS	Corn, Dry	Roug-hage	Urea	Lime-stone	Crude Protein	Calcium	Effective Fiber	Fat	Sulfur	Max Roug-hage	Min Urea	Max Lime-stone
Base Case	0.74	-	29.7%	56.0%	12.0%	0.3%	2.0%	0.0	0.0	0.0	**760.7**	0.0	**61.6**	**408.7**	**85.9**
	0.92	-	29.7%	56.0%	12.0%	0.3%	2.0%	0.0	0.0	0.0	**350.5**	0.0	**56.6**	**426.3**	**68.2**
	1.01	-	29.7%	56.0%	12.0%	0.3%	2.0%	0.0	0.0	0.0	**145.4**	0.0	**54.1**	**435.1**	**59.4**
Without Urea Minimum	0.74	1.24	29.5%	56.5%	12.0%	0.0%	2.0%	0.0	0.0	0.0	**755.9**	0.0	**61.5**	0.0	**85.9**
	0.92	1.30	29.5%	56.5%	12.0%	0.0%	2.0%	0.0	0.0	0.0	**345.6**	0.0	**56.5**	0.0	**68.3**
	1.01	1.32	29.5%	56.5%	12.0%	0.0%	2.0%	0.0	0.0	0.0	**140.5**	0.0	**54.1**	0.0	**59.5**
Maximum Roughage <=15%	0.74	1.84	30.3%	52.4%	15.0%	0.3%	2.0%	0.0	0.0	0.0	**735.2**	0.0	**61.2**	**408.4**	**84.7**
	0.92	1.69	30.3%	52.4%	15.0%	0.3%	2.0%	0.0	0.0	0.0	**325.4**	0.0	**56.2**	**426.0**	**67.1**
	1.01	1.62	30.3%	52.4%	15.0%	0.3%	2.0%	0.0	0.0	0.0	**120.5**	0.0	**53.8**	**434.8**	**58.3**
Maximum Roughage <=9%	0.74	-6.08	30.0%	58.8%	9.0%	0.3%	2.0%	0.0	0.0	**481.0**	**447.6**	0.0	**211.6**	**474.0**	**49.0**
	0.92	-6.14	30.0%	58.8%	9.0%	0.3%	2.0%	0.0	0.0	**504.2**	**25.0**	0.0	**213.9**	**493.4**	**29.6**
	1.01	-6.03	26.9%	61.8%	9.0%	0.3%	2.0%	0.0	0.0	**500.4**	0.0	0.0	**212.1**	**469.2**	**26.4**
Maximum Limestone <=2.5%	0.74	0.43	30.1%	55.1%	12.0%	0.3%	2.5%	0.0	0.0	0.0	**747.1**	0.0	**61.4**	**408.8**	**85.3**
	0.92	0.34	30.1%	55.1%	12.0%	0.3%	2.5%	0.0	0.0	0.0	**337.2**	0.0	**56.4**	**426.5**	**67.6**
	1.01	0.30	30.1%	55.1%	12.0%	0.3%	2.5%	0.0	0.0	0.0	**132.2**	0.0	**53.9**	**435.3**	**58.8**
Maximum Limestone <=1.5%	0.74	-0.43	29.4%	56.8%	12.0%	0.3%	1.5%	0.0	0.0	0.0	**774.3**	0.0	**61.7**	**408.6**	**86.5**
	0.92	-0.34	29.4%	56.8%	12.0%	0.3%	1.5%	0.0	0.0	0.0	**363.9**	0.0	**56.8**	**426.2**	**68.8**
	1.01	-0.30	29.4%	56.8%	12.0%	0.3%	1.5%	0.0	0.0	0.0	**158.6**	0.0	**54.3**	**435.0**	**60.0**

*Due to the non-linearity of the model, caution is advised when interpreting these shadow values.

Table 12: Economically Optimal WDGS/DDGS Real Price Ratio to Switch from WDGS to DDGS

		Corn Price ($/bu)		
		2	2.78	4.18
DDGS/Corn Real Price Ratio	0.8	1.38	1.33	1.29
	1	1.33	1.29	1.25
	1.2	1.3	1.26	1.23

Table 13: Manure Disposal Cost Scenarios

Manure Disposal Cost Parameter	Unit	Base Case	Scenario #							
			1	2	3	4	5	6	7	8
Land Accessible for Disposal	acres/mile	500		N/A	500	500	500		500	500
MDC taken into Account?	Yes/No	yes	yes		yes	yes	yes	yes	yes	yes
Corn	%	45	45	N/A		45	45	45	45	45
Soybean	%	45	45	N/A		45	45	45	45	45
Corn Silage	%	10	10	N/A		10	10	10	10	10
Application Rate Scenario	A/B	A	A	N/A	A		A	A	A	A
Size of operation	# Head	1,000	1,000	N/A	1,000	1,000			1,000	1,000
Value of P205	$/lb	0	0	N/A	0	0	0	0		0
Value of Nitrogen	$/lb	0	0	N/A	0	0	0	0		
Hourly Cost of Disposal	$/hr	150	150	N/A	150	150	150	150	150	150
Tank Size	gal	6,000	6,000	N/A	6,000	6,000	6,000	6,000	6,000	6,000
Loading Time	min/load	12.11	12.11	N/A	12.11	12.11	12.11	12.11	12.11	12.11
Unloading Time	Min/acre	6.19	6.19	N/A	6.19	6.19	6.19	6.19	6.19	6.19
Incorporation Time	min/acre	2.75	2.75	N/A	2.75	2.75	2.75	2.75	2.75	2.75
Travel Speed (full load)	mph	14	14	N/A	14	14	14	14	14	14
Travel Speed (empty)	mph	17	17	N/A	17	17	17	17	17	17

*The shaded areas highlight changes from the base case assumptions.

Table 14: Hypothetical Application Rate Scenario B: Non-Constant Proportions across Hauling Distance

Application Rate Category	% of Crop Acres within Each Application Rate Category at Various Hauling Distances (miles)															
	1	2	3	4	5	6	7	8	9	10	15	20	25	30	35	40
< 150 lbs/ac Phos - Apply at Nitrogen Removal Rate	5%	10%	15%	20%	25%	30%	35%	40%	45%	50%	55%	60%	65%	70%	75%	80%
150-300 lbs/ac Phos - Apply at Phosphorus Removal Rate	25%	45%	50%	60%	65%	70%	65%	60%	55%	50%	45%	40%	35%	30%	25%	20%
> 300 lbs/ac Phos - Do not Apply	70%	45%	35%	20%	10%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%

APPENDIX C: MATLAB CODE

Primary '.m' File[15]

```
clear all
% Basics of FMINCON
% FMINCON finds a constrained minimum of a function of several variables.
%   FMINCON attempts to solve problems of the form:
%      min F(X)  subject to:  A*X  <= B, Aeq*X  = Beq  (linear constraints)
%       X                     C(X) <= 0, Ceq(X) = 0    (nonlinear constraints)
%                             lb <= X <= ub            (bounds)

%   X=FMINCON(FUN,X0,A,B,Aeq,Beq,LB,UB,NONLCON,OPTIONS) minimizes
with the
%   default optimization parameters replaced by values in the structure
%   OPTIONS, an argument created with the OPTIMSET function. See OPTIMSET
%   for details. Use OPTIONS = [] as a  place holder if no options are set.

% Options set within code
options=optimset('TolFun',1e-4,'TolX',1e-4,'MaxIter',300,'TolCon',1e-4);

%#########################################################################

% Define choice variables
% WDGS= x(1); DDGS = x(2); Corn Dry = x(3); Corn Silage = x(4)
% Soybean meal = x(5); Hay = x(6); Urea = x(7); Limestone = x(8)

%#########################################################################

% Load model data from Excel(file name, worksheet name, row#:column#)

% Scenario parameters
   fData = xlsread('DGS Model Data','ObjFuncData','E6:AH1000');
% 'A' Matrix (linear,inequality constraints)
   A = xlsread('DGS Model Data','Constraints and Matrices','D4:K15');
% 'B' Matrix (linear,inequality constraints)
   B = xlsread('DGS Model Data','Constraints and Matrices','C4:C15');
% 'Aeq' Matrix (linear,equality constraints)
   Aeq= xlsread('DGS Model Data','Constraints and Matrices','D19:K19');
% 'Beq' Matrix (linear,equality constraints)
   Beq= xlsread('DGS Model Data','Constraints and Matrices','C19:C19');
% Animal response functions
   ARfunctions=xlsread('DGS Model Data','Animal Response Coef','C28:L1033');
% Misc. manure disposal cost data
```

[15] The '%' symbol indicates a comment, not an executable command.

```
   MDCdata = xlsread('DGS Model Data','MDC Other','A4:E4');
% Crop removal rates - RRcr (lbs/acre)
   RRcr = xlsread('DGS Model Data','MDC Matrices','B6:D8');
% Acres of each crop available at each application rate category within each
   %mileage category 'm'
   ACmcr = xlsread('DGS Model Data','MDC Matrices','B16:AW18');
% Miles within each mileage category
   Mm=xlsread('DGS Model Data','MDC Input Data','C11:R11');
% Speed traveled to and from field
   speed=xlsread('DGS Model Data','MDC Input Data','C32:R33');

%*****************************************************************

% Set temp data files (matrices used in other .m files)
setappdata(0,'tempA',A);
setappdata(0,'tempB',ARfunctions);
setappdata(0,'tempC',MDCdata);
setappdata(0,'tempD',RRcr);
setappdata(0,'tempE',ACmcr);
setappdata(0,'tempF',Mm);
setappdata(0,'tempG',speed);

%################################################################

% Choose which feeds ingredients are available. Enter upper bound if available
% and zero for unavailable. ONE OF THE TWO DGS TYPES MUST BE EQUAL TO
ZERO!

wdgs=0.5; % Wet Distillers Grains with Solubles
ddgs=0; % Dry Distillers Grains with Solubles
cd=1; % Dry Corn
cs=.15; % Corn Silage
hay=.15; % Hay (Alfalfa/Brome)
   % Base model constraints impose: 0.8 < hay+cs < 0.12 (matrix B).
   % However, an upper limit of .15 is set here so that when sensitivity
   %analysis is conducted upon feed ingredient constraints and the
   %model is run using the relaxed roughage constraint of .15, the program code
   %will allow this level to be reached.
sbm=1; % Soybean Meal
urea=.01; % Urea
   % Base model constraints impose a minimum of 0.003 (matrix B).
lime=.3; % Limestone (set higher than constraint imposed in matrix B to allow for
sensitivity analyzes with higher limits to be run)
```

```
%############################################################################

% Optimization loop

for j=1:1 % Scenario from fData, where j is the row from the fData matrix
    % to be optimized. j is set to run only scenario 1 (the base model).
      %However, if j was set to run through scenarios 1 through n (j=1:n),
      %the code would first find the optimal combiniation under scenario 1,
      %then 2, ..., then n.
      %For example if we wanted the model to run through
      %all combinations of DGS/corn price ratios, we would tell it to
      %run through scenario #27 (j=1:27). For each of these
      %scenarios all rows within the fData matrix are identical with
      %the exception of the DGS price.

    fDataUse = fData(j,:); %which set of scenario parameters to use
    setappdata (0,'temp1f',fDataUse);

    % These constraint values overwrite those established in the 'B'
      %matrix above. Used for sensitivity analyzes of base model
      %nutrient and feed ingredient constraints.
    B(1,1)=-fDataUse(25); % Sets calcium constraint
    B(5,1)=fDataUse(26); % Sets fat constraint
    B(8,1)=fDataUse(27); % Sets max roughage constraint
    B(12,1)=-fDataUse(28); % Sets urea min constraint
    B(6,1)=fDataUse(29); % Sets sulfur constraint
    B(11,1)=-fDataUse(30); % Sets min Crude protein constraint

    % Helps with starting values for DGS
    if (fDataUse(11)/fDataUse(12) >= 1.2) %DGS/Corn price ratio >=1.2
        a=3;
    elseif (fDataUse(11)/fDataUse(12) <= .70) %DGS/Corn price ratio <=.70
        a=1;
    else
        a=2;
    end

    % Establishes: starting values; lower bounds; and upper bounds,
      %respectively
    x0= [(wdgs/a+.01); (ddgs/a+.01); (cd/2+.01); (cs/2+.01); (sbm/2+.01);...
        (hay/2+.01); (urea/2+.01); (lime/2+.01)];
    lb = [0; 0; 0; 0; 0; 0; 0; 0];
    ub = [wdgs;ddgs; cd; cs; sbm; hay; urea; lime];
```

```
%Runs optimization program
   [x,fval,exitflag,output,lambda,grad,hessian]...
      = fmincon('ProfitFunction',x0,A,B,Aeq,Beq,lb,ub,[],[]);

   exitflag = exitflag

%##########################################################################

   %Output matrices and vectors
   xj(:,j) =x; %Ration formulation
   Profitj(:,j)=-fval; %Maximized profit
   exitflagj(:,j)=exitflag; %Exit flag
   lambda_ineqlij(:,j)=lambda.ineqlin; %Shadow values for inequality constraints
   lambda_eqlinj(:,j)=lambda.eqlin; %Shadow values for equality constraints
   lambda_lowerj(:,j)=lambda.lower; %Shadow values for lower bounds
   lambda_upperj(:,j)=lambda.upper; %Shadow values for upper bounds
   other(:,j)=[getappdata(0,'tempI');getappdata(0,'tempJ')]; %DOF & DMI
   excretion(:,j) =[getappdata(0,'tempK');getappdata(0,'tempL');...
      getappdata(0,'tempM');getappdata(0,'tempN');...
      getappdata(0,'tempO')]; %Manure excretion data

   %Check for 2nd order conditions
   for ii=1:length(x0)
   %Determinant # ii:
   DetCheck(ii)=det(hessian(1:ii,1:ii));
      if DetCheck(ii)<0 DetCheckNeg(ii)=1;
      else DetCheckNeg(ii)=0;
      end %if DetCheck(ii)<0 DetCheckNeg(ii)=1;
      end %for ii=1:length(x0)
   'sum(DetCheckNeg)';
   sumDetCheckNeg=sum(DetCheckNeg)

   sumDetCheckNeg(:,j)=sumDetCheckNeg;

 end %end of fdata scenario loop

   sum(sumDetCheckNeg)
```

Supporting '.m' File

```
function [P]=ProfitFunction(x)

format short
format compact

%###########################################################################

% Retrieve data from temp files
A=getappdata(0,'tempA');
ARfunctions=getappdata(0,'tempB');
MDCdata=getappdata(0,'tempC');
RRcr = getappdata(0,'tempD');
ACmcr = getappdata(0,'tempE');
Mm=getappdata(0,'tempF');
speed=getappdata(0,'tempG');
fDataUse = getappdata(0,'tempH');

%###########################################################################

% Define varibles from fDataUse:
SW=fDataUse(1); % Starting weight (lbs)
Mdgs=fDataUse(2); % Miles of DGS transport (the transport distance for corn is
  %assumed to be zero). A Mdgs value greater than zero was only used to
  %generate figures J1 and J2
CMwdgs=fDataUse(3); % Cost of transporting 1lb DM WDGS 1 mi
CMddgs=fDataUse(4); % Cost of transporting 1lb DM DDDGS 1 mi
%fDataUse(5)& fDataUse(6) - these excel columns were used to calculate (3)
  %and (4) above.
YC=fDataUse(7); % Daily yardage costs
r=fDataUse(8); % Yearly interest rate
Cfs=fDataUse(9); % Cost of purchased feeder steer ($)
Pwdgs=fDataUse(10); % Price of WDGS
Pddgs=fDataUse(11); % Price of DDGS
Pcd=fDataUse(12); % Price of corn, dry
Pcs=fDataUse(13); % Price of corn silage
Psbm=fDataUse(14); % Price of soybean meal
Phay=fDataUse(15); % Price of hay
Purea=fDataUse(16); % Price of urea
Plime=fDataUse(17); % Price of limestone
Py=fDataUse(18); % Base ouput price ($/lb)
s=fDataUse(19); % Which row of animal response function parameters to use
  %from ARfunctions matrix?
mdc=fDataUse(20); % Are manure disposal costs being incorporated?
  %1=yes & 2=no
```

```
n=fDataUse(21); % # Head
CF_nitrogen=fDataUse(22); % Commercial fertilizer value of nitrogen ($/lb)
CF_P205=fDataUse(23); % Commercial fertilizer value of P205 ($/lb)
Nutrient_valued=fDataUse(24); % 1 = both nitrogen and P205 are valued
    % & 2 = only nitrogen is valued

%###################################################################

% Define the objective function to be optimized
    % Profit = R-FC-VC-Cfs-MDC-K

%###################################################################

% R: Revenue
Y=1250; % Finished weight (lbs)
R=Py*Y;

%###################################################################

% FC: Feed costs
% FC= sum(Vi*Xi)*DMI*DOF, where Vi=(Pi+Ti). Pi = price of feed i and Ti =
    %transport cost for feed i.
% Ti = (Mi*(Cost per mile per lb dry matter), where Mi is the miles DGS is
    %transported (corn transport is assumed zero).

% Vi
Vwdgs=Pwdgs+(Mdgs*CMwdgs);
Vddgs=Pddgs+(Mdgs*CMddgs);
Vcd=Pcd;
Vcs=Pcs;
Vsbm=Psbm;
Vhay=Phay;
Vurea=Purea;
Vlime=Plime;

% DMI and DOF
ADG=ARfunctions(s,1)+ARfunctions(s,2)*x(2)*100+ARfunctions(s,3)*(x(2)*100)^2 ...
    +ARfunctions(s,4)*x(1)*100+ARfunctions(s,5)*(x(1)*100)^2;
DMI=ARfunctions(s,6)+ARfunctions(s,7)*x(2)*100+ARfunctions(s,8)*(x(2)*100)^2 ...
    +ARfunctions(s,9)*x(1)*100+ARfunctions(s,10)*(x(1)*100)^2;
DOF=(Y-SW)/ADG;

setappdata(0,'tempI',DOF); % used in output matrix, 'other'
setappdata(0,'tempJ',DMI); % used in output matrix, 'other'
```

```
FC=(Vwdgs*x(1)+Vddgs*x(2)+Vcd*x(3)+Vcs*x(4)+Vsbm*x(5)+Vhay*x(6)+Vurea*x(7
)...
   +Vlime*x(8))*(DMI)*(DOF);

%########################################################################

% VC: Other variable costs
Loans = Cfs+(.5*FC); % Cost of purchased feeder steer + half the feed costs
VC=(YC+(Loans*(r/365)))*DOF; % Daily yardage cost plus daily interest charges

%########################################################################

% MDC: Manure Disposal Costs

%************************************************************************

% Excretion Functions

% Converts DMI, SW and BW (average body weight), defined above, to units
  %specified within ASAE (2005) excretion equations
DMIg = DMI*453.59; % dry feed per day (g)
SWkg = SW*.45359; % Live body weight at start of feeding period (kg)
SRW=478; % Standard reference weight for expected final body fat(kg)-- 478
  %for Choice, 28% marbling; 462 for Select, 26.8% marbling
BWkg = ((Y+SW)/2)*.45359; % Average live body weight for feeding period (kg)
Ykg =Y*.45359; % Finished weight in kg

%.........................................................................

% Phosphorus Excretion

% Concentration of phosphorus in diet
Cp = -(A(3,1)*x(1)+A(3,2)*x(2)+A(3,3)*x(3)+A(3,4)*x(4)+A(3,5)*x(5)+A(3,6)*x(6)...
  +A(3,7)*x(7)+A(3,8)*x(8)); %lbs of phosphorus per lb dry feed

% Phosphorus excretion function and Disposal Cost Function
P =((Cp*DMIg*DOF)-(10*(Ykg-
SWkg))+(.0592*DOF*(BWkg^0.75)*((SRW/Ykg*0.96)^0.75)...
  *((Ykg-SWkg)/DOF)^1.097))/1000; % Total kg of phosphorus excreted per finished
animal

Pe=P*n*2.2; % Total lbs of phosphorus excreted per operation
P205=Pe*2.3; % Converts phosphorus to P205
```

```
%.............................................................................................................................

% Nitrogen Excretion

% Concentration of crude protein
Ccp=-(A(11,1)*x(1)+A(11,2)*x(2)+A(11,3)*x(3)+A(11,4)*x(4)+A(11,5)*x(5)...
   +A(11,6)*x(6)+A(11,7)*x(7)+A(11,8)*x(8)); %g of protein per g dry feed

% Nitrogen excretion function and Disposal Cost Function
N = ((Ccp*DMIg*DOF/6.25)-(41.2*(Ykg-SWkg))+(.243*DOF*(BWkg^0.75)...
   *((SRW/(Ykg*0.96))^0.75)*(((Ykg-SWkg)/DOF)^1.097)))/1000;
   % Total kg of nitrogen excreted per finished animal

Ne=N*n*2.2; % Total lbs of Nitrogen excreted per operation

%.............................................................................................................................

% Total Manure Excretion

DMD=80;% dry matter digestibility of the ration (%) (ASAE 2005)

TMkg=(((DMIg*DOF*(1-DMD/100)+(DOF*20.3*(.06*BWkg)))/1000)/.08)*n;
   % Total kg of Dry matter excreted for operation
   % Note that TM = total solids/%solids.  Assumed moisture = 92% (ASAE 2005).

TM=(TMkg*2.2)/8.3; % Total Gallons of Manure, 8.3lb=1gal

%.............................................................................................................................

% Data assembled for output matrix, 'excretion'
Nitrogen = Ne/n; % lbs per finished animal
Phos = Pe/n; % lbs per finished animal
T.Manure = (TM*8.3)/n; % lbs per finished animal
setappdata(0,'tempK',Nitrogen);
setappdata(0,'tempL',Phos);
setappdata(0,'tempM',T.Manure);
setappdata(0,'tempN',Ccp); % Concentration of crude protein in diet
setappdata(0,'tempO',Cp); % Concentration of phosphorus in diet

%*********************************************************************

% Calculating manure disposal costs (MDC)
% MDC = (((LT+TT+IT+UT)*DC)-FertValue)/n; %Cost per finished animal

% Define variables from MDCdata matrix (used within this section)
DC= MDCdata(1); % Hourly manure disposal costs ($/hr)
```

```
lt=MDCdata(3); % Hours required to load 1 tank
ts=MDCdata(2); % Tank size (gal)
b=MDCdata(4); % Hours required to unload on 1 acre
inc=MDCdata(5); % Hours required to incorporate 1 acre

%..............................................................................................................

% Manure disposal loop - allocates the total quantity of manure produced by
  %the operation to accessible fields. Starts with field closest to the
  %feedlot and the crop with the highest nitrogen removal rate and
  %procedes through the loop until all manure is disposed of.

  % This loop calculates the number of loads going to each field (Loads)
  %as well as the transportation time (tt), unloading time (ut), and
  %incorporation time (it) for each field.

  GA=[];% Starting value for total gallons applied
  % Need something to check at the beginning of the 2nd if statement

  for m=1:16; % Mileage Category

   for c=1:3;% Crops 1-3;
    %1. Corn Silage
    %2. Soybeans
    %3. Corn for Grain


      for r=1:3; % Application rate category
       %1. Less than 150 lbs/ac Phos
       %2. 150-300 lbs/ac Phos
       %3. Exceeds 300 lbs/ac Phos

       % Establish applicable nutrient density
       if (r==1) % D1
          D=(Ne/TM);% Nitrogen Density (lbs/gal)
       elseif (r==2) % D2
          D=P205/TM; % P205 Density (lbs/gal)
       else
          D=1; % D3 - doesn't really matter what it is b/c RRcr = zero
       end
```

```
% Allowable gallons of manure application for each field (AGmcr)
AGmcr=(RRcr(c,r)/D)*ACmcr(c,r+3*(m-1));

% This if statement is to make sure that we don't dispose of more
%manure than we have.
RM=TM-(sum(sum(GA))); % # Gallons of manure remaining to be disposed of

if (AGmcr<=RM)% There is more manure to be disposed of than is
   %allowable on field 'mcr'
   GA(c,r+3*(m-1)) = AGmcr; % apply what is allowable
else
   GA(c,r+3*(m-1)) = RM; % apply remaining manure
end

%//////////////////////////////////////////////////////////////////////////////////////////

%Loads
Loads(c,r+3*(m-1))=(GA(c,r+3*(m-1))/ts);

%//////////////////////////////////////////////////////////////////////////////////////////

% ut

% This if statement is needed b/c otherwise, when RRcr=0, the
% formula used to calculate ut will yield division by zero.
if (RRcr(c,r)==0)% In principle this is for j=3, but more
   %generally stated
   ut(c,r+3*(m-1))=0;
else
   ut(c,r+3*(m-1))=((ts/(RRcr(c,r)/D))*b*Loads(c,r+3*(m-1)));
end

%//////////////////////////////////////////////////////////////////////////////////////////

% tt
hpmt = 1/speed(1,m); % Hours per mile - Travel speed to field
hpmb = 1/speed(2,m); % Hours per mile - Travel speed returning from field
tt(c,r+3*(m-1))=Loads(c,r+3*(m-1))*Mm(m)*(hpmt+hpmb);

%//////////////////////////////////////////////////////////////////////////////////////////

% it
% This if statement is needed b/c otherwise, when RRcr=0, the
% formula used to calculate ut will yield division by zero.
if (r==3)
  it(c,r+3*(m-1))=0;
```

```
        else
          it(c,r+3*(m-1))=inc*GA(c,r+3*(m-1))/(RRcr(c,r)/D);
        end

      end% end of application rate loop
    end% end of crop loop
  end% Miles loop
%............................................................................................................................

LT=lt*sum(sum(Loads)); % Loading time
UT=sum(sum(ut));% Unloading time
TT=sum(sum(tt)); % Transportation time
IT=sum(sum(it)); % Incorporation time

%............................................................................................................................

%Establishing the value of the nutrients in the manure (VN)

if (Nutrient_valued==1)% both nitrogen and phosphorus are valued
  VN= (CF_nitrogen*Ne) +(CF_P205*P205);
else %only nitrogen is valued
  VN = CF_nitrogen*Ne;
end

%Note: when neither are valued, CF_nitrogen and CF_P205 both equal zero

%............................................................................................................................

%Is the model being run under the scenario where MDC are not being incorporated?

if(mdc==1)%yes
   MDC= (((LT+TT+IT+UT)*DC)-VN)/n; %MDC per finished animal
else
   MDC=0;
end

%#######################################################################

%K: Fixed costs
 K=0;

%#######################################################################

%Objective function
P = -(R-FC-VC-Cfs-MDC-K);
parm=x;
```

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REFERENCES

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