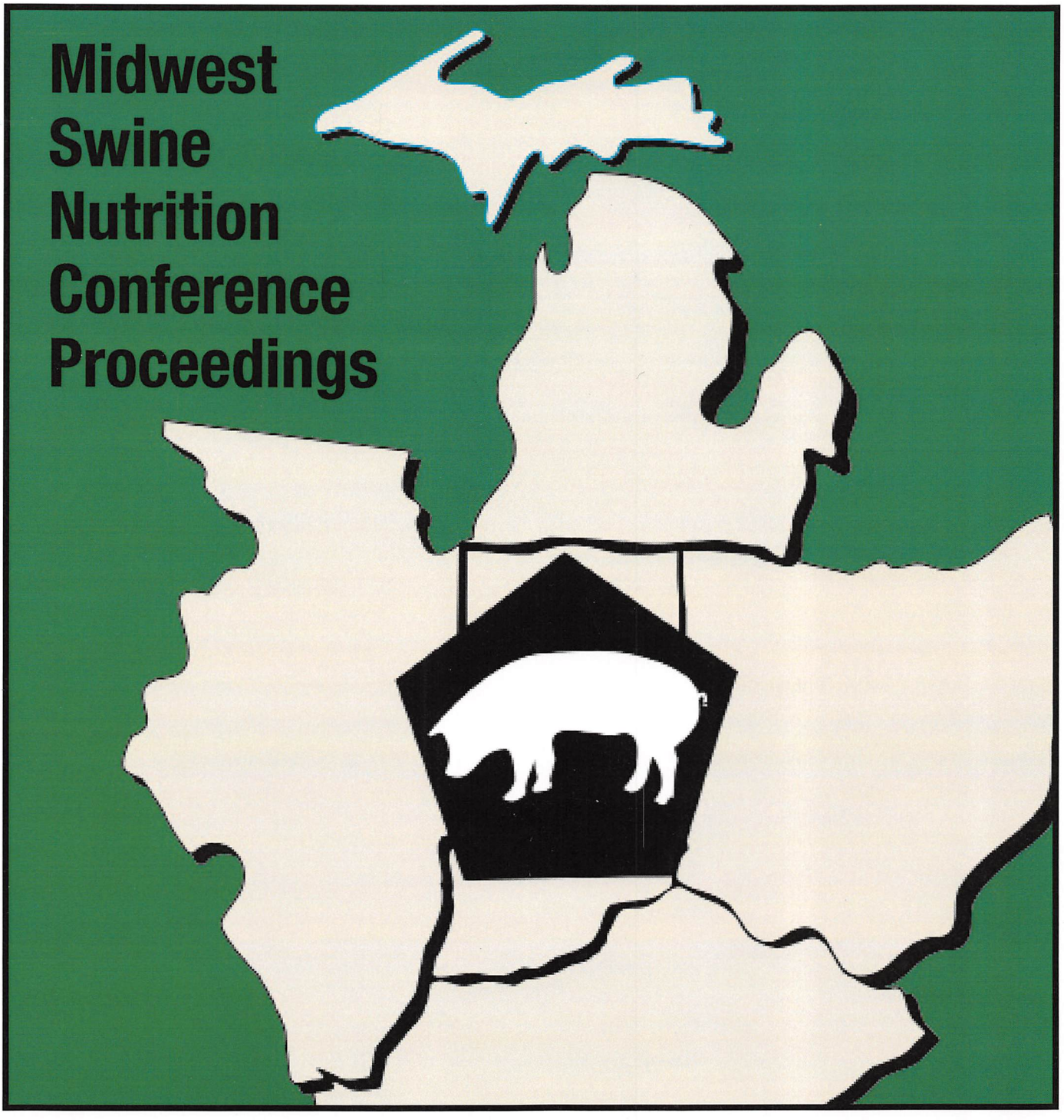
Midwest Swine Nutrition Conference Proceedings



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Economics of Production, Processing and Marketing*

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The North American pork industry has and continues to undergo structural change due to rapid change in product characteristics, worldwide production and consumption patterns, technology, size of operation, and geographic location. Production once dominated by independent, family-based, small-scale firms is now led by large firms that are tightly aligned across the production and distribution chain. Contracts and other types of marketing arrangements are increasingly important across nearly every market level—from input supply and seed stock to finished food product markets. The traditional production and marketing firms and linkages still exist, but are gravitating to niches for differentiated products that may command a premium from some consumers. As the industry has become more industrialized, specialized and managerially intense, location options have expanded beyond traditional production regions.

There is great diversity in how pork is produced in North America and the world, but common themes are emerging. As in North America, many countries worldwide are experiencing major structural changes in their production sectors, and environmental concerns in production are nearly universal. Technology adoption is rapid, and a "world standard" is evolving to greater commonality of technology, size of production units, processing and quality.

This analysis assesses the global competitiveness of the North American pork and livestock industries by focusing on:

- Industry cost and coordination structures;
- Market demand for source verification, traceability and emerging markets;
- Government regulations, policy and standards; and
- Cost drivers, including feed costs; nutrition and production technology innovations; crop-livestock synergies; financing and capital access/ cost; and energy costs and ethanol production.
- Risk management
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Coordination and Value Chain Structures

Contracts and other types of marketing arrangements are increasingly important across every market level of the pork industry—from input supply and seed stock to finished food product markets. They provide greater coordination and more detail specification than do arm's-length open market transactions. These marketing tools enable firms to reduce costs of buying and/or selling meat and livestock; reduce risk exposure; enhance access to credit; increase supply chain information flow; ensure closer quality specifications and product traceability; ensure market access; increase flexibility in responding to customer needs; enhance opportunities for product differentiation and branding; increase food safety and biosecurity assurances; and enhance operating efficiency.

** Abstracted from "The Future of Animal Agriculture in Noth America," A farm Foundation Project, 2006. Boehlje was a c0author and coordinator of the chapter on this topic in this book.*

Many firms participate in contracts to assure market access. With the dramatic decline in spot market transactions in hogs during recent years, market access has been a concern, especially for producers located in fringe production areas. Likewise, packers outside major production regions can use contracts to secure necessary supplies. Producers in key production regions use contracts to ensure access to buyers without incurring substantial search costs when animals are ready for harvest. Packers also contend that marketing contracts allow them to source better quality and more consistent quality of animals.

The substantial horizontal contracting growth among hog producers suggests that contracts enable large production operations to get larger. However, numerous other factors contribute to the large horizontal expansion and consolidation in hog production. These include profits that attract external capital and advances in genetics, health, nutrition and production management that increase economies of scale. Many smaller operations have been able to remain in hog production by contracting with horizontal and vertical integrators. Integrators provide production services, capital and risk management options that encourage smaller operations to continue to participate in livestock production.

Some people perceive large operators as beneficiaries of marketing agreements and contracts. Others contend that marketing agreements reduce spot market liquidity, lessen the availability of market information for efficient price discovery, and adversely affect smaller operations. It is unclear whether contracts and marketing agreements are a result of, or a factor in, increased concentration of firms involved in meat and livestock markets. It is also unclear if the benefits from improved supply coordination offset any potential costs that the decreased use of open markets may cause.

Asymmetries in market information and captive supply are continuing sources of controversy in the livestock industry. But empirical evidence on market power and pricing suggests that processor advantages are inconsistent and not widespread.

In summary, new forms of value chain coordination enable large firms to shift risk, leverage capital, increase profitability, improve product uniformity and traceability, exploit comparative advantages, reduce costs, and provide more direct price signals to value chain participants. Industry advocates maintain that increased information flow enhances overall market efficiency and better enables the industry to compete globally and domestically. Critics object to the lower prices allegedly paid to family farms and the loss of access in the marketplace. More intensive value chain coordination mechanisms provide a direct method to verify and ensure particular production, processing and marketing practices, and procedures to enhance product quality, safety and credence for consumers. Some traditional producers that have lost share to large-scale tightly aligned supply chains are targeting value-added niche markets that differentiate the product by how or by whom the animal was raised. These markets are either direct farmer to consumer or are more coordinated than traditional open markets. The ultimate beneficiaries of new value chain coordination mechanisms are consumers who pay less for products of standardized quality or who pay more for differentiated products.

Source Verification, Identity Preservation and Food Traceability Systems

Consumer concerns about access to and the availability of reliably safe food sources have prompted changes in the global meat and livestock industries. Issues include use of hormones, animal health, bio-terrorism threats, food safety, international trade, credence attributes (which consumers cannot determine from viewing or consuming the product), and improving supply chain management. Economic incentives pushing these new systems, in large part, originate from the international meat marketplace. Increasingly, consumers worldwide are demanding assurance of safe meat products, and assurance that production systems are capable of tracing sources of potential food safety concerns in a timely and precise manner. Countries and producers able to provide such assurances will have a considerable competitive advantage in world meat markets.

Food safety is a key risk for all segments of the livestock industry. Food products that make people ill, or in a worst-case scenario cause death, can quickly destroy brand value, the most valuable asset of a branded-food product company. Supply chain management using a traceback system, combined with quality-assurance procedures such as Hazard Analysis and Critical Control Point (HACCP), facilitates control of the system to minimize the

chances of a food contaminant, or to quickly and easily identify the sources of contamination. Traceability is increasingly a key motivation for controlled origination of raw materials from certified suppliers to implement a supply chain philosophy.

Food products that can be traced through production, processing and marketing have strong appeal to consumers. Such products are seen as having greater food safety standards and assurances. For the livestock industry, animal identification and traceability are critical for effective management and rapid arrest of animal health and disease concerns. National animal and meat traceability programs are being implemented. The discovery of *bovine spohngiform encephalopathy* (BSE) in Canada and the United States in beef has increased the urgency of having such systems in place to achieve timely and accurate trace-back of animals.

New Markets, Niche Markets

Consumers have diverse preferences. Many consumers, particularly those who are more affluent, are demanding extrinsic food attributes not related to food safety or federal grading standards. Some consumers are interested in issues related to animal production, such as animal welfare, antibiotic free, growth hormones, use of genetically modified organisms and free-range production. Developed economies, such as the United States, Canada, Japan and the European Union (EU), have some consumers that fit this profile.

Many of these characteristics cannot be verified through physical testing of the product; consumers must rely on supplier reputation, or process verification and certification programs. This requires animal segregation throughout production, processing and marketing. These practices may increase the cost of production, relative to traditional commercial production methods, i.e., reduced growth efficiency due to not using feed additives in pork production. Differentiated markets and different pricing/product valuation structures are necessary to support such production practices.

Impacts of Regulations

A sound regulatory framework protects the health and environment of citizens, contributes to economic growth, and promotes investments that, in turn, improve a nation's productivity and its people's standard of living. A dysfunctional regulatory system hinders productivity and innovation and reduces competitiveness and job opportunities. Protecting health and the environment is not necessarily a tradeoff for competitiveness and innovation. A slow, burdensome regulatory system can actually harm human health and the environment by stifling the very innovations that could yield improvements.

Increasingly, every aspect of animal production is regulated at some level of government—municipal, state, or federal. Farm-level regulations include disposal of dead stock, environmental (including site selection, waste management and protection of water resources), medicated feeds, sale and use of livestock medicines, transportation of compromised animals, animal identification, animal cruelty, and nutrient management. At the processing level, regulations include livestock and poultry carcass grading, and food safety, all of which fall under various national regulatory authorities.

The intent of any regulatory framework is to protect the country's citizens while keeping its industries competitive by promoting investments and increasing productivity. The challenge for the future is to seek a balance of regulations that do not compromise competitiveness by imposing too many costs on various segments of the value chain.

Traditionally, U.S. public policies in the livestock industries have been directed at improving economic efficiency and "leveling the playing field," especially in protecting the interests of producers relative to those of packers and processors. The Packers and Stockyards Act of 1921 has financial, trade practice and competition provisions. The Agricultural Marketing Act of 1946 and related statutes provide the authority for federal grading and standards activities, provision of market news information, and other market-facilitating functions.

The Livestock Mandatory Reporting Act of 1999 was introduced to correct perceived market failures, which were seen as particularly detrimental to smaller livestock operations. Voluntary reporting of spot market prices facilitated price discovery for many years in the United States. The adequacy of the system was called into question as more trade took place through marketing or formula pricing arrangements that were not reported under the voluntary system. Under mandatory reporting, large meat packers are required to report information on all cattle, hog and sheep purchases and beef and lamb sales transactions. A recent Government

Accountability Office (GAO) study indicated mandatory reporting has given the market additional information about prices for different kinds of sales transactions.

In recent years, various state and federal policies have been proposed in the United States to restrict certain types of organization and market conduct in the livestock and meat industries. For example, there have been proposals to prohibit packer ownership of livestock and to restrict certain marketing practices, such as privately negotiated marketing agreements that allow packers to know the supply of animals coming to their plant for more than 14 days in advance. At the federal level, such market conduct regulations are under the purview of USDA's Grain Inspection, Packers and Stockyards Administration (GIPSA). Small-farm advocates have long contended that USDA was not enforcing the laws intended in the original 1921 act, and had pressured states to enact legislation. A 2006 GAO study found that GIPSA had not established an adequate control structure and environment to allow the agency to oversee and manage its investigative activities.

Several states have anti-corporate farming laws to correct market imbalances, particularly between large meat packers and smaller livestock producers. Some laws seek to preserve the ability of livestock producers to operate independently without having to become aligned with a particular buyer through ownership, contract or other vertical alliance. Debate over these policies will continue—one side arguing that such policies do little more than impede economic efficiency and freedom to contract, and the other arguing the policies are needed to prevent abuse of market power and preserve family farms.

Feed Costs and Future Nutritional Technology

Feed is the highest operating cost—50 percent to 60 percent of most animal production operations. Any change in feed costs impacts profitability. Use of antibiotics, feed modifiers and specialized feed ingredients has increased animal productivity. Research is underway to determine specific nutrient requirements for specific genetics. Recent biotechnology techniques have provided insight to the mechanisms controlling metabolism at the cellular level, allowing for development of diet modifiers or feed formulations to affect nutrient retention. These tools appear to be cost effective, contributing to increased production and/or an increased price for an improved quality of product.

Reducing the crude protein level in mongastric diets and supplementing with essential synthetic amino acids have been important dietary changes for hogs. These shifts have reduced nitrogen excretion levels 25 percent to 50 percent, and reduced emissions of specific gases and odors from animal housing units. Reducing protein from plant sources and balancing the amino acid profile with synthetic amino acid reduces nitrogen excretion of excess amino acids. Use of the synthetically derived enzyme, phytase, which is also present in wheat and barley, can reduce phosphorus excretion up to 20 percent to 25 percent with no significant cost increases.

Many pork producers use specific feed ingredients or enzymes to reduce phosphorus levels in manure because of regulations on phosphorus applications to agricultural land. Animal production in areas with these regulations is at a cost disadvantage, compared to areas in the world without such regulations. Some nutrition technologies influence the quality of the final animal product, which can potentially fit niche markets and result in value-added returns.

Production Technology Innovations and Crop-Livestock Synergies

The primary method of manure management in North America is recycling the nutrients back into crop production. If grains can be produced with the correct amounts of nutrients, and rations can be formulated to meet a specific animal's requirements, the need to supplement diets will be reduced, reducing excess excretion of nutrients that need to be stored, treated and used on cropland. Costs would also be reduced, as would the pressure on the environment.

The potential exists for relationships between animal and crop producers—the animal producer purchases grain from the crop operation, which then receives manure nutrients. This trade may result in economic advantages for each operation. In a long-term scenario of fertilizer costs increasing and fertilizer resources diminishing, the use of organic fertilizers may be much more valuable. In farms, regions or countries that import grain to feed animals because not enough is produced locally, manure nutrient management is more challenging. Operations

are looking to treat, compost or generate energy by burning or biogas production from the manure to reduce the volume of nutrient-containing material that has to be hauled to fields.

Technologies are available to enhance the efficiency of animal production, and control the impact of animal production on the environment. Large operations can better afford and manage manure treatment technologies, particularly those with high fixed costs. They can spread the costs over a larger volume of product and have sufficient volume to potentially sell value-added products. Environmental regulations requiring significant restrictions on producers will force the structure of the animal industry to much larger operations. Some technologies in nutrition or housing designs are size neutral and will not affect the structure of the industry, as long as the technologies are cost effective.

Financing and Capital Access/Cost

Capital markets are relatively efficient in allocating funds to those who successfully manage risk and generate the highest returns. This generalization is more accurate in its application to the processing, wholesaling and retailing segments of the value chain than to smaller firms in the production sector. Firms that do not use modern technology, that are smaller scale, have relatively high costs, and/or have not used accepted tools and techniques to manage operating risks may encounter difficulty accessing financing at reasonable costs.

The dramatic globalization of the capital/financial markets has dissipated the relative advantage the North American livestock market had over global competitors in accessing the capital markets at a competitive cost. The significant barriers and resulting higher costs that once restricted the flow of funds across country borders have declined. Firms that can show competitive returns are less constrained in access to financing in the form of debt or equity funds, regardless of their location in the world.

The North American livestock industries, particularly in Canada and the United States, are well positioned in terms of global competitiveness and cost structure for access to financing and the capital markets. The capital market institutional structure, combined with efficient and effective risk management and mitigation procedures for borrowers and lenders, aids credit access and the flow of equity capital to the sector. Economies of size, combined with the multi-plant replicate expansion strategy and the broader adoption of strategies to manage operating risk, enable larger-scale firms to exhibit lower cost and expand more rapidly than smaller-scale firms. The efficiency and product flow scheduling, quality management, traceability and risk mitigation advantages of more tightly aligned value chains have and will continue to transform the industries from open-access market coordination to vertical linkages through ownership, contracts or strategic alliances.

Energy Costs and Ethanol Production

High energy prices increase costs of production. The United States has an animal production system that requires more fossil fuels than less confined systems. Some regions or countries will see higher energy prices in the form of higher cost transportation costs to import grain or higher irrigation costs to pump water to grow grain. The impact of increased energy prices will fall more heavily on the United States and Canada, relative to countries using less energy in production, processing and retailing.

Nitrogen fertilizer is a major component of the energy consumed in producing feed. From 1982 to 1997, the number of livestock farms decreased 50 percent and the number of confined animal units (1,000-pound liveweight per unit) increased 10 percent. This has led to situations where there is excess application of farm manure nutrients and an increasing number of crop farms depending totally on external sources for nutrient needs. The increasing value of animal manure could result in a slowing, if not reversal, of the trend toward more separated grain and livestock production farms.

Corn-based ethanol has become a popular fuel source in the United States. Ethanol production is a nonfeed demand for corn. Distillers grain, a coproduct of ethanol production, is used as an animal feed and will replace some corn and soybean meal as a source of calories and protein in rations. This is particularly true for ruminants—beef and dairy cattle—that can utilize the high-fiber distillers grain, and to a lesser extent for monogastrics, hogs and poultry. A negative impact of distillers grain and other coproducts is a concentration of and therefore higher excretion of nutrients, especially phosphorus.

This will require more land for manure application to meet environmental regulations, or a costly treatment of manure to recover phosphorus for distribution off-farm. The increased costs of production due to higher feed costs from increased demand for corn for ethanol will be felt mostly in North America, decreasing the region's world competitive position.

Risk Management

Lenders are particularly conscious of risk and increasingly impose discipline on their customers to be efficient and utilize the best risk management strategies. This suggests that an increasing proportion of production will occur in integrated production/distribution systems—not only to capture the efficiencies of such a system, but also to reduce risk exposure in market prices, quantity and quality. Consequently, it will be increasingly difficult for traditional independent producers to access adequate funds unless they adopt current technology and use management strategies to reduce their and their lenders' risk exposure.

The livestock industries will likely face new instabilities and financial risks from factors not previously considered. The increased interdependence that comes with supply chain alliances trades price and quality risk for relationship risk, such as a plant shutdown, contract termination or disease outbreak. There will also be increased variability in feed ingredient prices because of growing competition with the energy and industrial-use markets for corn and soybean products.

Globalization brings greater dependency on export markets, which increases instability from exchange rate fluctuations, changing political policies in foreign countries, and weather conditions worldwide. Trade disputes and disease outbreaks will have greater impacts on the North American industry, as demonstrated by the outbreak of foot-and-mouth disease (FMD) in the United Kingdom and the case of BSE in Canada and the United States. In addition, countries such as Brazil and Argentina are expanding production and exporting animal proteins into the global markets.

Final Comment

In general, relatively low input costs, including feed, combined with modern technology and well-developed input and product markets, institutions and distribution systems, enable North America to be a competitive producer and supplier of quality pork products. However, North America will be increasingly challenged in commodity production and lower value and quality animal products by Brazil in beef, pork and poultry. It will be important for the North American livestock industry to maintain and increase its emphasis on quality attributes and differentiated products to expand its position in the global animal product markets and industries.

Environmental and odor problems may be significant deterrents to locating livestock production and distribution systems in various areas of North America. But is highly likely that much of the expansion in production to meet increasing worldwide demand for animal proteins will be by North American or European integrated production/distribution firms or alliances, regardless of where the production and plants are located. North America cannot rest its competitive case on low cost alone—it must adapt products to specific markets and provide enhanced quality control and health and safety assurances.

The consolidation trend to fewer and larger pork operations is expected to continue. The economies of scale in production and processing are significant and will drive the optimal size of the facility, as well as the firm. Firm-level economies will be captured through effective supply chain management that improves cost efficiency and control, food safety and quality, and the ability to respond to consumer demands. Quality concerns will also drive more systemized, micro-managed production and distribution processes to reduce product variability and improve conformance with quality standards and consumer expectations of uniform product attributes. Technology will provide new efficiencies and information to better manage the system. Concerns about food safety and a drive to qualified suppliers and traceback will increase pressures and payoffs of tighter coordination along the production and distribution chain.

Pork and livestock production and processing are increasingly mobile. Capital and technology can move anywhere in the world. North American firms can and have invested in production-processing centers in regions with comparative advantages. Likewise, such production-processing centers in North America may have foreign ownership. The livestock production/distribution industries are clearly becoming global in scope and in product

exports and imports. In the future, only a few global livestock firms are likely to dominate world production and processing, and will source and sell products globally.

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DDGS in Swine Diets – Does it Impact Processing of Cured Bellies and Eating Quality of Pork?

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Summary

Studies have shown that feeding a high level of DDGS to growing-finishing pigs causes softer bellies that result from greater percentages of polyunsaturated fatty acids in body fat. Some of the belly firmness problems and elevated iodine values in carcass fat can be overcome by withdrawing the DDGS from the diet during the final 4 to 6 weeks of the finishing period. In our studies, the softer bellies, greater percentages of polyunsaturated fatty acid in the carcass fat, and higher iodine values from pigs fed high levels of DDGS did not negatively impact processing yield of cured bellies or eating quality of bacon, bratwurst sausage, or loin chops.

Introduction

Numerous ethanol plants have been built over the past several years. These plants have a high demand for corn for the production of ethanol which has resulted in a substantial increase in corn prices, hence greater feed costs and reduced profits for swine producers. Expanded ethanol production has resulted in large quantities of distillers dried grains with solubles (DDGS) being produced. This byproduct has economic value as a replacement for a portion of the more expensive corn and soybean meal in swine diets.

When the large amounts of DDGS became available as an economic feed ingredient, one of the major questions that surfaced was how much DDGS could be included in diets for growing-finishing swine without reducing growth performance and carcass quality. Another concern was whether feeding large amounts of DDGS, which contains 8-10% of a highly unsaturated fat, would cause soft bellies in pork carcasses. The packing industry is known to discriminate against pork carcasses from hogs fed high-oil corn or such diets that have large amounts of polyunsaturated fat because those types of diets result in greater amounts of linoleic acid and other polyunsaturated fatty acids in the carcass fat. Bellies from such carcasses are known to be softer and are claimed by packers to be more difficult to slice into bacon. Also, very little was known about the eating quality of pork from pigs fed large amounts of DDGS and having carcasses with increased amounts of polyunsaturated fat.

The NCCC-42 Study

A large collaborative study was conducted a few years ago by a group of swine nutritionists at nine universities to provide some answers to these questions. This group, called the North Central Coordinating Committee on Swine Nutrition (NCCC-42) followed a carefully designed experimental protocol and fed diets containing 0, 15, 30, or 45% DDGS from a single source to 560 pigs from 33 to 121 kg. The diets (Table 1) were fed during three phases with diet changes made at 60 and 91 kg. Carcass traits and fatty acid composition of the body fat were determined along with measurements of belly firmness from representative pigs in the study.

The results of that study were presented at this conference in 2009 (Cromwell, 2009) and will soon be published in the Journal of Animal Science (Cromwell et al., 2011). Table 2 gives an overview of some of the main results. Increasing the DDGS level to 30 or 45% of the diet resulted in a slight decrease in growth rate (linear, $P < 0.02$) but it did not affect daily feed intake or feed efficiency. Carcass dressing percent was not affected by DDGS level. Carcass backfat was less ($P < 0.02$) in pigs fed the two higher levels of DDGS and percent fat-free lean in the carcass increased slightly (linear, $P < 0.06$) in pigs fed DDGS.

Belly firmness was determined using an apparatus fabricated by the participating stations (Figure 1) and flexure of the belly was measured according to procedures described by Rentfrow et al., (2003). Briefly, the belly is centered, skin down, on the supporting PVC pipe and allowed to slump. Vertical flex is the distance from the top of the pipe to the slumped end of the belly; whereas, lateral flex is the distance from a point directly below the center of the pipe to the interior edge of the slumped belly. Both lateral and vertical flex measures (Table 2) indicated that the bellies became softer and more flexible as level of DDGS increased in the diet (linear, $P < 0.003$). Analysis of the backfat confirmed that the saturated and monounsaturated fatty acids decreased linearly and polyunsaturated fatty acids increased linearly as dietary DDGS level increased ($P < 0.001$), and these changes resulted in linear increases in iodine values ($P < 0.001$). Plotting the iodine values against dietary DDGS at the nine participating experiment stations indicated that iodine value increased 0.432 units for every 1 percent inclusion (i.e., 4.32 units for each 10 percent inclusion) of DDGS in the diet (Figure 2).

Although there is no consistent standard for acceptable iodine value, NPPC (2000) recommended a maximum iodine value of 70, whereas Boyd et al. (1997) suggested a value of 74 as maximum. Based on the relationship in this study, DDGS inclusion rates of 13 and 22% would have resulted in iodine values of 70 and 74, respectively.

Belly Processing and Sensory Evaluation

The University of Kentucky pigs that were involved in the NCCC-42 study (15 pigs per treatment) were used to determine processing characteristics of the cured bellies and sensory evaluation of bacon, bratwurst sausage, and pork chops from pigs fed the four levels of DDGS (McClelland, 2010; McClelland et al., 2009, 2010a,b).

Bellies from each pig were thawed, skinned, boxed, and transported to a commercial facility (Burgers Smokehouse, California, MO) where they were weighed, then pumped with a commercial brine and allowed to drain to approximate 110% of their green weight. After they were smoked and thermally processed according to the plant's protocol, the bacon slabs were chilled overnight. The following morning, they were reweighed, pressed, then individually sliced with a high-speed slicer at nine slices per inch. All slices and pieces were collected from each belly, boxed separately, and transported back to the University of Kentucky Meats Laboratory where incomplete slices, comb marks, or any other slices determined to be defective were removed. The remaining slices that were deemed marketable as bacon were weighed to determine slicing yield ([weight of marketable bacon slices / weight of smoked bacon slab] ×100).

Representative slices of fresh bacon were evaluated for shatter characteristic of the fat between the lean. Slices were then fried under standard conditions to determine distortion of cooked bacon. Other slices were cooked on a griddle to target 40% of their weight for sensory evaluation by a trained, eight-member panel.

Boston butts and shoulder picnics were used to prepare bratwurst style sausage. After grinding these two cuts separately, fat percentage of each was determined and the two ground cuts were blended to target 30% fat in the sausage. A commercial blend of seasonings was added, then the sausage was overwrapped with oxygen-permeable polyvinyl chloride and stored to determine shelf life stability. The remaining sausage mix was stuffed into natural casings and made into links for sensory evaluation. Color scores and TBARS were determined on the sausages over a 7-day period. Sausage links were steeped in water and cooked to an internal temperature of 71° C for sensory evaluation by the trained, eight-member panel.

Loin chops (1 in. thick) were prepared from the loin at the 10th rib. They were cooked on a clam-shell grill to an internal temperature of 70° C and served to the eight-member panel for sensory evaluation.

Table 3 shows the results of the belly processing. Included in this table are the belly flex measures and fatty acid composition and iodine values of the belly fat of the 15 pigs per treatment that were from our station. The trends were similar to those of the entire NCCC-42 study with linear responses in these traits ($P < 0.03$ to $P < 0.001$) associated with level of DDGS in the diet. The most interesting finding was, contrary to what is generally claimed by the packing industry, we did not find any reduction in slicing yield in the softer bellies. In fact, slicing yield was highest in bellies from pigs fed the 30% DDGS diet (78% vs. 73.5% in pigs fed the corn-soybean meal diet. Bacon shatter scores improved linearly ($P < 0.001$) with increased belly softness, and there were no differences in cooking shrink or distortion score of the fried bacon. Sensory evaluation scores were unaffected by increased belly softness caused by feeding high levels of DDGS.

Color scores of bratwurst sausage indicated, as expected, a darker color, loss of redness, and less vivid color over the 7-day storage period (Table 4). None of these color traits at 7-days of storage were affected by DDGS treatment. TBARS of sausages, however, were influenced by treatment with scores that increased linearly ($P < 0.02$) with increased level of DDGS fed, suggesting that shelf life may be shortened for sausages containing more unsaturated fat. The higher percentages of polyunsaturated fat in pork resulting from increasing amounts of DDGS in the diet improved texture (linear, $P < 0.004$) and juiciness (linear, $P < 0.04$) of the sausages.

Taste panel members were unable to differentiate any differences in tenderness, juiciness, or off-flavor among loin chops from pigs fed the four levels of DDGS (Table 5).

Withdrawal of DDGS in Late Finishing

A second experiment was conducted at the University of Kentucky to further evaluate the effects of feeding a high level of DDGS to pigs for the entire growing-finishing period and to see if withdrawal of DDGS for varying time periods during the late finishing period would influence performance, belly firmness, processing of cured bellies, and eating quality of bacon and loin chops (Ulery, 2010; Ulery et al., 2010a,b).

The study involved 168 crossbred pigs. Seven dietary treatments were evaluated, which included a corn-soybean meal control diet, a similar diet with 45% DDGS fed continuously to the end of the experiment, or three treatments in which the DDGS was removed during the final 2, 4, or 6 weeks of the experiment followed by the feeding of a corn-soybean meal diet. Two additional treatments were the same two diets but with 5% added tallow. Each treatment was evaluated with six replications of three or five pigs per pen. Diets (Table 1) were fed in three phases from 37 to 120 kg body weight. The diets were formulated on a standardized ileal digestible (SID) lysine basis with 0.81, 0.70, and 0.55% SID lysine during the three phases. The experiment was terminated on a replication basis when the average weight of the control pigs reached 120 kg. Three pigs per pen were killed for carcass information.

Most of the procedures for determining belly firmness, processing of cured bellies, and characteristics and eating quality of bacon and loin chops were similar to those of the previous experiment. The addition of tallow had no positive impact on any of these traits, so that aspect of the study is not included in this discussion.

Table 6 shows the results of the DDGS withdrawal portion of the study. Over the entire experiment, daily gain and daily feed intake were reduced ($P < 0.05$) by about 8 to 9% in pigs fed DDGS continuously, but efficiency of feed utilization was not affected. Daily gain and daily feed intake improved linearly ($P < 0.05$) with increasing time of DDGS withdrawal. In this study, carcass dressing percent was reduced by DDGS feeding ($P < 0.05$), but withdrawal of DDGS improved dressing percent in a quadratic manner ($P < 0.05$).

As in the earlier NCCC-42 study, belly flex measurements were negatively impacted by DDGS feeding ($P < 0.01$), but they improved linearly ($P < 0.03$) with increasing time of DDGS withdrawal. When DDGS was withdrawn for 6 weeks, the belly flex measurements were the same as those of the control pigs. The percentage of polyunsaturated fatty acids in the backfat increased ($P < 0.05$) when DDGS was fed, but the changes were moderated with length of DDGS withdrawal time (linear, $P < 0.05$). Iodine values in backfat were higher in DDGS fed pigs ($P < 0.05$), but values became less with increased time of withdrawal (linear, $P < 0.05$). The 4-week withdrawal brought iodine values to near 70, a level that is considered acceptable by NPPC (2000) and the 2-week withdrawal brought iodine values to near 74, considered acceptable by Boyd et al. (1997).

Bellies from all of the carcasses were processed at the same commercial plant as before and procedures were as previously described. Slicing yield was determined and fresh bacon slices were scored for shatter. Slices were then fried and scored for distortion, cook loss, and shrink, and were evaluated by a trained, eight-member sensory panel.

Table 7 shows that DDGS inclusion, which resulted in softer bellies, had no affect on slicing yield of smoked bellies, which is the same as what we found in the previous experiment. The softer bellies actually produced bacon with improved shatter scores ($P < 0.05$). However, after frying, there was more weight loss, more shrink in length, and greater distortion ($P < 0.05$) in bacon from pigs fed DDGS ($P < 0.05$). Withdrawal of DDGS had only minor effects on these measurements. The sensory panel was unable to determine any significant differences in texture or off-flavor in bacon from any of the treatment groups.

There were no differences in color, marbling, or firmness of fresh loin or in TBARS of loin chops among the five treatment groups (Table 8). Actually, TBARS at 7-days were numerically lower in loin chops of pigs fed DDGS than in pigs fed the diet without DDGS. Shear force of cooked chops indicated no differences in tenderness among treatments. The taste panel scored the chops from the DDGS pigs to be slightly less tender and less juicy than chops from the control pigs, but these differences were small, not statistically significant, and well within an acceptable range of tenderness and juiciness.

The finding in these two studies that belly firmness was not associated with sliding yield of cured bellies is in contract to what is generally considered by the packing industry that soft bellies are difficult to slice and result in belly slabs that yield less marketable bacon slices (i.e., poor slicing efficiency). Looking at this in another way, we plotted slicing efficiency of individual bellies from our two studies (McClelland, 2010; Ulery, 2010) against the iodine value of those bellies. The individual belly data illustrates that although slicing efficiency was quite variable (ranging from 94.4 to 33.4%), there did not appear to be any relationship between the iodine values and slicing efficiency (Figure 3).

In summary, these studies clearly show belly softness, polyunsaturated fatty acid percentages, and iodine values of backfat and belly fat are elevated by feeding DDGS to finishing pigs. Some of the belly softness problems and elevated iodine values can be overcome by withdrawing the DDGS from the diet during the final 4 to 6 weeks of the finishing period. In our study, a 4-week withdrawal produced acceptable iodine values (approximately 70); however, inclusion of a hard fat (beef tallow) to the diet was totally ineffective in improving belly firmness or reducing iodine values of pigs fed a high level of DDGS. Under the conditions of this study, the softer bellies, increased polyunsaturated fatty acids, and higher iodine values did not negatively impact bacon processing or eating quality of bacon, bratwurst sausage, or loin chops in pigs fed a high level of DDGS.

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Table 1. Composition of diets (%, as fed basis)[1]

	NCCC-42 Study Phase III Diets				Univ. of Ky Study Phase III Diets	
DDGS in diet:	0%	15%	30%	45%	0%	45%
Corn	82.71	72.10	61.50	50.89	83.54	50.84
Soybean meal, dehulled	15.00	10.67	6.33	2.00	14.00	2.00
DDGS[2]	--	15.00	30.00	45.00	--	45.00
L-lysine-HCl	--	0.065	0.130	0.195	--	0.24
L-threonine	--	--	--	--	0.04	--
L-tryptophan	--	0.012	0.024	0.036	--	0.03
DL-methionine	--	--	--	--	0.05	--.
Dicalcium phosphate	1.24	0.83	0.41	--	1.30	--
Ground limestone	0.58	0.85	1.13	1.40	0.60	1.42
Salt	0.30	0.30	0.30	0.30	0.30	0.30
Vitamins, trace minerals	0.15	0.15	0.15	0.15	0.15	0.15
Tylan-40	0.025	0.025	0.025	0.025	0.025	0.025
Total	100.00	100.00	100.00	100.00	100.00	100.00
Calculated analysis						
Protein, %	14.0	15.0	16.0	17.0	13.6	17.8
Total lysine, %	0.67	0.70	0.74	0.78	0.64	0.71
SID lysine, %[3]	0.58	0.58	0.58	0.58	0.55	0.55
SID threonine, %	0.44	0.45	0.46	0.47	0.46	0.46
SID tryptophan, %	0.13	0.13	0.13	0.13	0.12	0.12
SID methionine+cystine, %	0.45	0.48	0.51	0.54	0.48	0.48
Fat, %	3.7	4.6	5.5	6.4	2.6	6.1
NDF, %	9.3	13.1	16.9	20.6	9.3	17.1
Ca, %	0.57	0.57	0.57	0.57	0.59	0.59
Total P, %	0.56	0.56	0.55	0.54	0.57	0.56
Digestible P, %	0.25	0.25	0.25	0.25	0.26	0.26
ME, Mcal/kg	3.34	3.34	3.34	3.35	3.34	3.31

[1]Only the Phase III diets are shown.

[2]The analyzed composition of the DDGS used in the two studies was, respectively (%, as is basis): dry matter-90.1, 92.1; crude protein-26.3, 28.1; crude fat-9.4, 10.3; acid detergent fiber-14.0, 15.9; neutral detergent fiber-34.6, 26.8; crude fiber-6.5, 7.2; ash-5.1, 4.3; calcium-0.03, 0.07; phosphorus-0.86, 0.90; sulfur- 0.68, 0.58; lysine-0.96, 0.73; tryptophan-0.18, 0.18; threonine-0.99, 0.96; methionine+cystine-1.01, 0.84, isoleucine-1.02, 1.04; valine-1.35, 1.35.

[3]The true (or standardized) ileal digestible (SID) lysine requirement (NRC, 1998) for pigs at the midpoint of Phases I, II, and III was 0.80, 0.67, and 0.53%, respectively.

Table 2. Performance, carcass traits, belly flex, and fatty acid composition and iodine values of backfat from pigs fed four levels of DDGS[1,2]

	DDGS, %				
Item	0	15	30	45	Significance
Initial weight, kg	32.6	32.7	32.4	32.5	
Final weight, kg	120.4	121.6	120.6	119.3	
Average daily gain, kg	0.95	0.95	0.93	0.91	Linear, P < 0.02
Average daily feed intake, kg	2.74	2.77	2.69	2.71	
Feed/gain	2.89	2.88	2.91	2.95	
Slaughter weight, kg	121.5	122.9	120.5	119.8	
Hot carcass weight, kg	90.8	91.9	89.9	89.0	Linear, P < 0.05
Dressing percent	74.8	74.8	74.7	74.3	
Backfat, 10th rib, mm	22.5	22.7	21.4	21.6	Linear, P < 0.02
Loin eye area, sq cm	47.4	47.4	46.1	45.4	
Carcass fat-free lean, %	51.9	52.2	52.4	52.1	Linear, P < 0.06
Belly flex[3]					
Lateral, cm	11.9	8.6	8.4	6.6	Linear, P < 0.001
Vertical, cm	26.1	27.4	28.2	28.7	Linear, P < 0.003
Fatty acids in backfat[4]					
Saturated, %	38.2	36.0	33.5	30.4	Linear, P < 0.001
Monounsaturated, %	48.0	44.9	42.3	39.7	Linear, P < 0.001
Polyunsaturated, %	13.7	19.0	24.1	29.7	Linear, P < 0.001
Iodine value of backfat[4,5]	64.5	70.8	77.1	84.3	Linear, P < 0.001

[1]Adapted from Cromwell et al., 2011; NCCC-42 study involving nine stations.
[2]Performance data based on 28 replications of four to six pigs per pen; carcass data, fatty acid composition, and iodine values based on 28 replications of two pigs per pen; belly flex data based on 12 replications of two pigs per pen from six stations.
[3]A lower lateral score and a higher vertical score indicate a softer, more flexible belly.
[4]Average of inner and outer backfat.
[5]The iodine values of the inner backfat (61.1, 68.2, 74.7, 82.2) were significantly less (P < 0.001) than those of the outer backfat (67.9, 73.6, 79.6, 85.8).

Table 3. Bacon traits and sensory evaluation of bacon from carcasses of pigs fed four levels of DDGS[1,2]

	DDGS, %				
Item	0	15	30	45	Significance
Belly flex[3]					
Lateral, cm	10.3	7.1	6.0	4.7	Linear, P < 0.01
Vertical, cm	27.7	29.2	29.8	30.8	Linear, P < 0.03
Fatty acids in belly fat					
Saturated, %	37.4	35.6	33.5	31.6	Linear, P < 0.001
Monounsaturated, %	49.2	47.5	44.1	43.6	Linear, P < 0.001
Polyunsaturated, %	12.4	17.0	22.4	24.8	Linear, P < 0.001
Iodine value of belly fat	65.4	69.7	75.8	79.5	Linear, P < 0.001
Belly traits					
Green weight, kg	4.79	5.05	4.67	4.69	
Pumped weight, kg	5.31	5.53	5.08	5.02	
Smoked weight, kg	4.55	4.85	4.36	4.41	
Recovered bacon slices, kg[4]	3.37	3.54	3.39	3.29	
Slicing yield, kg	73.5	72.8	78.0	73.7	
Bacon traits					
Shatter score of fresh slices[5]	4.37	4.10	3.55	3.54	Linear, P < 0.001
Cooking shrink, %	6.61	6.84	6.65	7.19	
Distortion score, fried bacon[6]	2.68	2.46	2.51	2.56	
Sensory attributes[7]					
Texture[8]	7.98	7.77	7.79	7.64	
Off-flavor[9]	3.23	3.28	2.79	3.61	

[1]McClelland (2010) and McClelland et al. (2009, 2010a,b).
[2]Bellies from three replications of five pigs per pen (Kentucky data only).
[3]A lower lateral score and a higher vertical score indicate a softer, more flexible belly.
[4]Deemed as marketable bacon after comb marks and incomplete or damaged pieces were removed.
[5]Scored 0 to 6, with 0 representing no visual cracks or shattering in the fat of the bacon slices and scores of 1 to 6 representing increases in severity of shattering in the fat of the slices.
[6]Scored 1 to 5, with 1 representing a flat slice after cooking and larger scores representing increased severity of curling. A score of 5 represented complete curling of the slice.
[7]Performed by a trained, eight-member panel.
[8]Texture score of 0 to 15 with 0 = extremely tough, 15 = extremely tender or crumbly.
[9]Off-flavor score of 0 to 15 with 0 = no off-flavor, 15 = intense off-flavor.

Table 4. Color scores, TBARS, and sensory evaluation of bratwurst sausage from carcasses of pigs fed four levels of DDGS[1,2]

	DDGS, %				
Item	0	15	30	45	Significance
L* color score[3]					
Day 0	52.58	52.27	52.11	53.53	
Day 7	50.10	50.04	50.70	51.15	
a* color score[4]					
Day 0	13.49	13.60	12.78	12.01	
Day 7	8.75	8.73	8.94	8.30	
b* color score[5]					
Day 0	19.13	18.67	17.40	17.43	Linear, $P < 0.06$
Day 7	17.83	17.62	17.10	17.12	
Chroma score[6]					
Day 0	23.41	23.10	21.58	21.17	
Day 7	19.87	19.67	19.30	19.03	
TBARS, mg/kg[7]					
Day 0	0.99	0.98	0.94	0.92	
Day 7	1.03	0.95	1.18	1.38	Linear, $P < 0.02$
Sensory attributes[8]					
Texture[9]	8.46	6.97	7.38	6.52	Linear, $P < 0.004$
Juiciness[10]	6.70	7.50	7.38	8.19	Linear, $P < 0.04$
Off-flavor[11]	2.61	2.76	2.56	2.82	

[1]McClelland (2010) and McClelland et al. (2009, 2010a,b).
[2]Three replications of five pigs per pen.
[3]Degree of lightness with 0 = black and 100 = white.
[4]Degree of redness with negative values = green and positive values = red.
[5]Degree of yellowness with negative values = blue and positive values = yellow.
[6]Calculated as the square root of ($a^{*2} + b^{*2}$). A higher number represents a more vivid color.
[7]TBARS represent the amount of fatty acid oxidation that has occurred. A higher score represents greater oxidation of the fat due to presence of more unsaturated fatty acids, which may reduce shelf life and increase the chances of off-flavor.
[8]Sensory evaluation was performed by a trained, eight-member panel.
[9]Texture score of 0 to 15 with 0 = soft and mushy, 15 = hard and chewy.
[10]Juiciness score of 0 to 15 with 0 = extremely dry, 15 = extremely juicy.
[11]Off-flavor score of d 0 to 15 with 0 = off-flavor and 15 = intense off-flavor.

Table 5. Sensory evaluation of loin chops from carcasses of pigs fed four levels of DDGS[1,2]

	DDGS, %				
Item	0	15	30	45	Significance
Sensory attributes[3]					
Texture[4]	8.34	7.89	8.13	8.63	
Juiciness[5]	5.09	5.20	5.06	5.68	
Off-flavor[6]	6.62	5.55	5.50	5.46	

[1]McClelland (2010) and McClelland et al. (2009, 2010a,b).
[2]Three replications of five pigs per pen.
[3]Sensory evaluation was performed by a trained, eight-member panel.
[4]Texture score of 0 to 15 with 0 = extremely tough, 15 = extremely tender.
[5]Juiciness score of 0 to 15 with 0 = extremely dry, 15 = extremely juicy.
[6]Off-flavor score of 0 to 15 with 0 = off-flavor and 15 = intense off-flavor.

Table 6. Effects of feeding a high level (45%) of DDGS and withdrawal of DDGS from the finisher diet on performance, carcass traits, belly firmness, fatty acid composition, and iodine number of body fat[1]

Diet:	Corn-Soy	DDGS	DDGS	DDGS	DDGS
Withdrawal of DDGS:	-	-	2-wk	4-wk	6-wk
Initial weight, kg	37.4	37.6	37.4	37.4	37.3
Final weight, kg[2]	122.4	116.4	120.4	120.8	120.2
Average daily gain, kg[2,3]	1.00	0.92	0.95	0.97	0.96
Average daily feed intake, kg[2,3]	2.80	2.55	2.68	2.93	2.78
Feed/gain	2.81	2.81	2.84	3.05	2.90
Slaughter weight, kg[2,3]	124.0	117.8	121.2	121.2	122.5
Hot carcass weight, kg[2,3]	93.0	86.5	91.0	90.7	91.3
Dressing percent[2,4]	75.0	73.4	75.1	74.8	74.5
Backfat, 10th rib, mm[3]	22.8	24.5	22.1	25.3	27.4
Loin eye area, sq. cm[2]	48.9	44.9	47.8	45.8	45.7
Carcass fat-free lean, %[2,4]	50.7	49.5	50.8	49.2	48.3
Belly flex[5]					
Lateral, cm[2,3]	15.0	11.3	12.1	13.0	15.2
Vertical, cm[2,3]	31.8	33.7	33.4	32.7	31.4
Fatty acids in backfat[6]					
Saturated, %[2,3]	41.6	33.5	35.3	38.2	38.8
Monounsaturated, %[2,3]	45.9	40.5	42.3	42.5	43.9
Polyunsaturated, %[2,3]	12.6	26.0	22.5	19.3	17.4
Iodine value of backfat[2,3]	60.9	78.8	74.3	70.4	67.3

[1]Performance data based on six replicates of three or five pigs per pen (n = 24/treatment); carcass data based on six replicates of three pigs/pen (n = 18/treatment).
[2]Corn-soybean meal vs. DDGS with no withdrawal ($P < 0.05$).
[3]Linear effect of withdrawal time ($P < 0.05$).
[4]Quadratic effect of withdrawal time ($P < 0.05$).
[5]A lower lateral score and a higher vertical score indicates a softer, more flexible belly.
[6]Average of inner and outer backfat.

Table 7. Effects of feeding a high level (45%) of DDGS and withdrawal of DDGS from the finisher diet on cured belly and bacon characteristics[1]

Diet:	Corn-Soy	DDGS	DDGS	DDGS	DDGS
Withdrawal of DDGS:	-	-	2-wk	4-wk	6-wk
Belly traits					
Green weight, kg	4.52	4.08	4.22	4.33	4.56
Pumped weight, kg	5.03	4.39	4.58	4.80	5.11
Smoked weight, kg	4.19	3.70	3.84	4.02	4.27
Recovered bacon slices, kg[2]	2.79	2.41	2.64	2.82	3.06
Slicing yield, %	66.1	65.6	69.3	69.2	70.3
Bacon traits					
Shatter score of fresh slices, %[3,4]	4.35	3.45	3.71	3.65	3.99
After bacon was fried					
Weight loss, %[3]	55.5	58.5	56.7	56.5	58.0
Shrink in length, %[3]	27.8	30.8	30.3	30.2	30.6
Distortion score[3,5]	3.16	3.52	3.49	3.53	3.45
Sensory attributes[6]					
Texture score[7]	3.07	3.00	3.00	3.11	2.99
Off-flavor score[8]	1.78	1.94	1.87	1.80	1.99

[1]Bellies from six replicates of three pigs per pen, or 18 bellies per treatment.
[2]Deemed as marketable bacon after comb marks and incomplete or damaged pieces were removed.
[3]Corn-soybean meal vs DDGS with no withdrawal ($P < 0.05$).
[4]Fresh bacon slices were given scores of 1 to 6, with 1 representing no visual cracks or shattering and scores of 2, 3, 4, 5, and 6 representing increases in severity of shattering within the fat of the bacon slice. A score of 6 represented a "spider-web" consistency of shattering.
[5]Cooked bacon slices were scored using a 5-point scale where 1 represented a flat slice after cooking, with higher scores representing increased severity of curling. A score of 5 indicated a slice that was completely curled with no flat areas on the slice.
[6]Taste panel evaluation was performed by a trained, eight-member panel.
[7]Texture scores: 1 to 5 with 1 = extremely tough and chewy, 3 = desirable, and 5 = very tender or crumbly.
[8]Off-flavor scores: 1 to 15 with 1 = no off-flavor and 5 = intense off-flavor.

Table 8. Effects of feeding a high level (45%) of DDGS and withdrawal of DDGS from the finisher diet on loin chop characteristics[1]

Diet:	Corn-Soy	DDGS	DDGS	DDGS	DDGS
Withdrawal of DDGS:	-	-	2-wk	4-wk	6-wk
Subjective scores[2]					
Color	2.94	2.89	2.53	2.78	2.67
Marbling	1.89	1.61	1.69	2.00	1.94
Firmness	2.94	2.89	2.67	2.83	2.78
TBARS, mg/kg[3]					
Day 0	0.64	0.59	0.59	0.59	0.59
Day 7	1.44	1.19	1.29	1.24	1.29
Shear force of cooked chops, kg	3.20	3.27	3.00	2.83	3.21
Sensory attributes of cooked chops					
Tenderness[4,6]	5.24	4.70	4.81	5.08	5.27
Juiciness[4]	5.02	4.64	4.61	4.99	4.91
Off-flavor[5]	0.50	0.38	0.43	0.31	0.39

[1]Loins from six replicates of three pigs per pen, or 18 loins per treatment.
[2]Color score of 1 to 10, with 1 = pale, pinkish gray to white and 10 = dark, purplish red. Marbling score of 1 to 10, with 1 = 1% marbling and 10 = 10% marbling. Firmness score of 1 to 5, with 1 = extremely soft and 5 = extremely firm.
[3]TBARS represent the amount of fatty acid oxidation that has occurred. A higher score represents greater oxidation of the fat due to presence of more unsaturated fatty acids; this may reduce shelf-life and increase the chances of off-flavor.
[4]Tenderness and juiciness scores: 1 to 5 with 1 = tough and dry; 5 = extremely tender and juicy.
[5]Off-flavor scores: 0 to 5 with 0 = no off-flavor; 5 = very intense off-flavor.
[6]Linear effect of withdrawal time ($P < 0.05$).

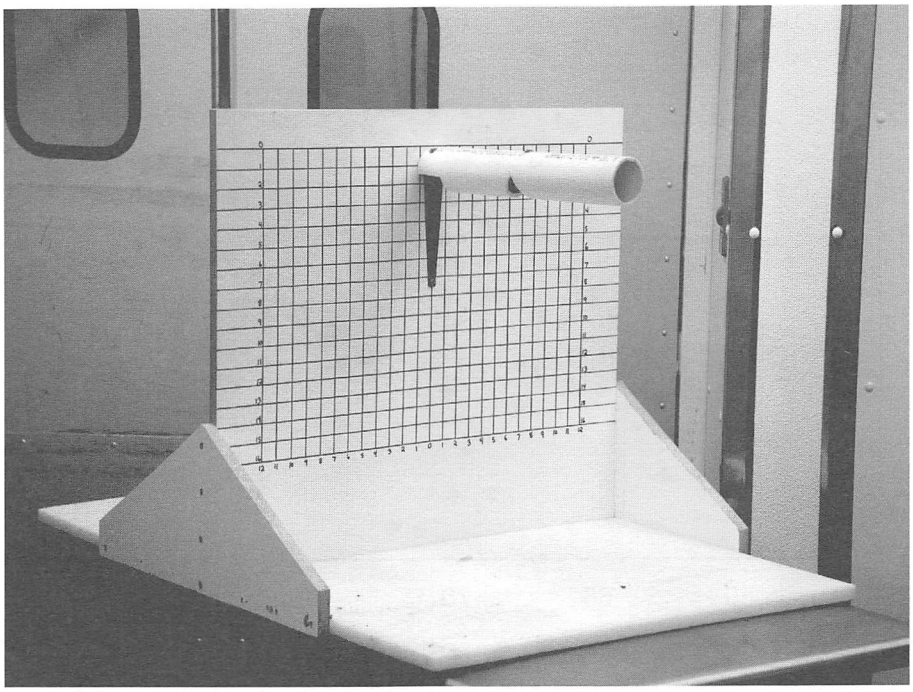

Figure 1. Apparatus that was fabricated by each station to quantify belly flex measurements. The numbers on the vertical and horizontal scales represent measurement units of 1 in. (2.54 cm.).

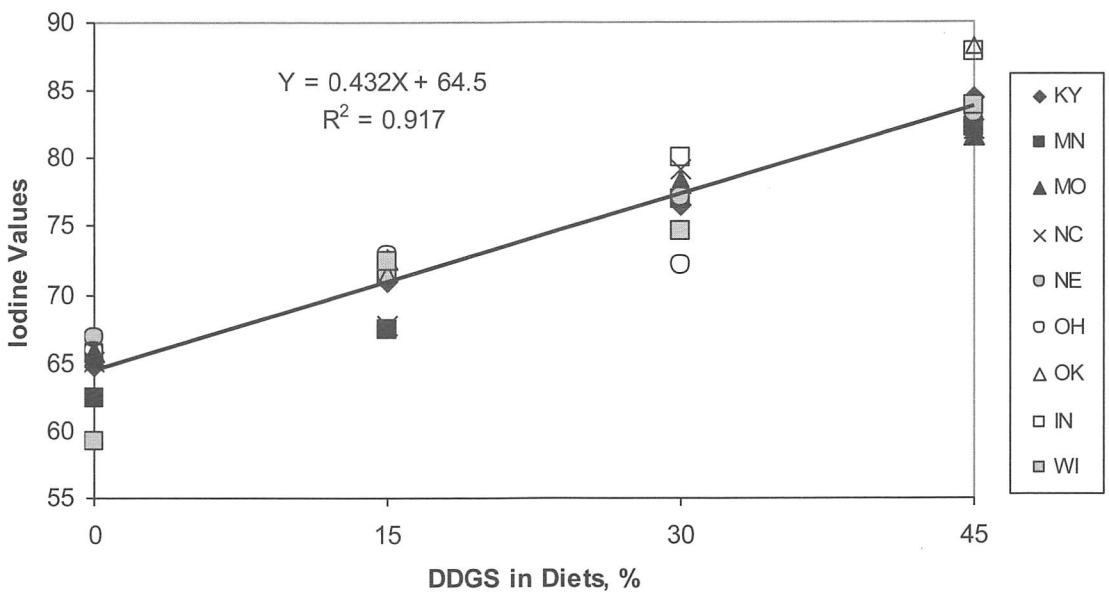

Figure 2. Iodine values in backfat (average of inner and outer backfat) of pigs fed corn distillers dried grains with solubles (DDGS) during the growing-finishing phase at nine experiment stations. The regression line indicates that the iodine value increased 4.32 units for every 10% increase in DDGS in the diet.

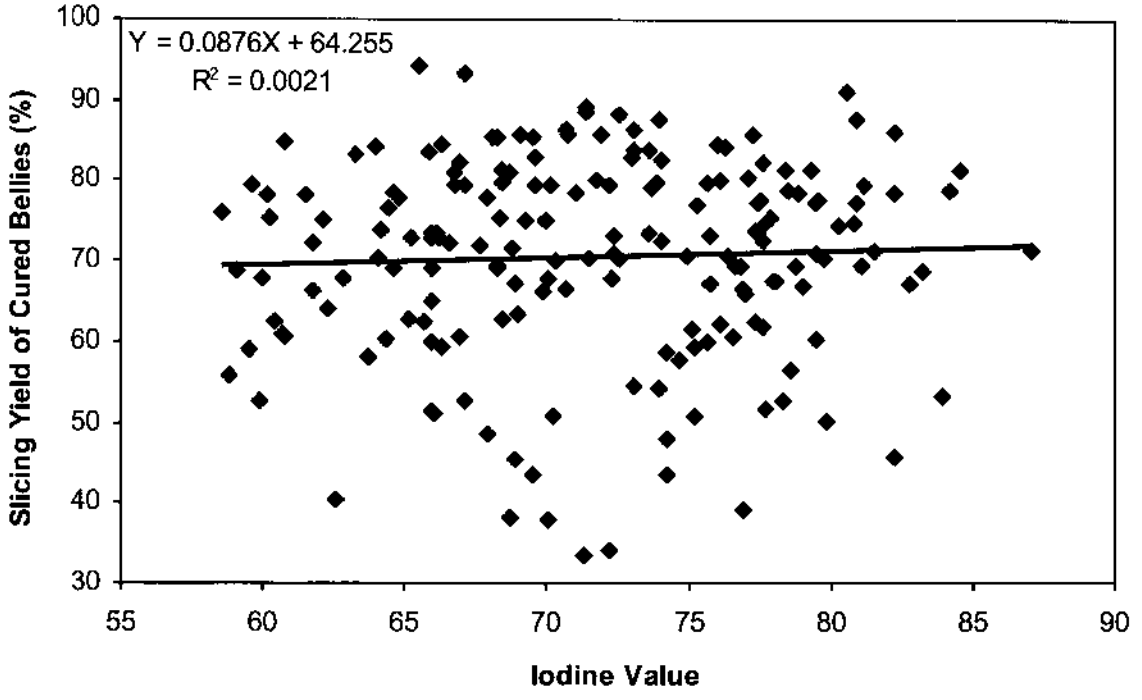

Figure 3. Relationship of iodine value (mean of inner and outer backfat and belly fat) and slicing yield of cured bellies. The data are from 182 bellies in the studies of McClelland (2010) and Ulery (2010). A nearly flat regression line and a low R^2 indicate that there was no relationship between the two traits.

Antibiotic Update and Perspective

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Summary

Since the late 1960's, antibiotic use in food animals, especially as it relates to the emergence, selection, propagation, and dissemination of antibiotic resistance (AR) among foodborne enteric bacteria, has dominated much of the public policy debate at the interface between animal agriculture and public health. In the past 10 years, there have been several important developments that have furthered this debate, suggesting that neither the problem, nor the perception of a problem (depending on one's view), is likely to go away soon. The following are of particular note: 1) the issuance by the World Health Organization (WHO) of the first list of "Critically Important Antibiotics" for use in human medicine in 2005, 2) the European Union (EU) ban on the use of antibiotics as growth promoters since 2006, 3) the pending (since 2008) final rule of the U.S. Food and Drug Administration (FDA) to ban extra-label use of cephalosporins in food-producing animals, and 4) the discovery of shared carriage of a multitude of bacteria such as Clostridium difficile or MRSA ST 398, be they resistant or not to antibiotics, among humans and food animal species. It seems quite apparent that science will continue to be needed in the near and distant future to address these concerns, to quantify the food safety risks (if and where they exist), and to pursue alternatives to antibiotics and mitigation strategies to combat AR as part of prudent food animal husbandry practices. Several developments in this developing and fluid area are highlighted in this paper.

Introduction

Antibiotic resistance (AR) among pathogenic and commensal enteric bacteria of food-animal origin has continued to serve as a focus of fierce debate in national and international scientific and political circles. Available evidence supports theories suggesting that the use of antimicrobials in animal agriculture leads to the favorable selection of resistant strains of bacteria within treated animals and within aggregated groups of treated animals (as it also does in human medicine). However, this measurable effect applies largely to periods while animals are being treated, and for short periods thereafter (Lowrance et al., 2007). Poorly understood are the longer-term effects reflecting the cumulative impacts of multiple uses in many animals, pens/barns, and farms over extended periods of time (Alali et al., 2009). Equally problematic is evidence from a number of studies that suggest shared carriage of resistant organisms (or, their subtypes) among humans and farm animals is perhaps less relatively less common than one might expect (Poole et al., 2005; Alali et al., 2010).

On the other hand, research and surveillance of AR relating to antibiotic use is often focused on the target pathogen in the animal (or human) and may not adequately reflect the public health risk (i.e., food safety) or be particularly useful for mitigating against, or reducing the levels of AR in the enteric bacterial community. Further, research directed at understanding ways to mitigate against antimicrobial

resistance, and surveillance programs directed at detecting and quantifying resistance as it becomes more persistent, often rely solely on simple estimates of AR prevalence (whether genotypic or phenotypic) among bacterial isolates from non-selective culture media (USDA, 2008). These approaches are often inadequate for observing, and quantifying the emergence, dissemination, and proliferation phases, and indeed require substantive persistence for prevalence estimates to become stable and repeatable, whether in research or surveillance settings. At such a point it may be too late to stem the tide of resistance, despite our best intentions.

Despite the limitations in capturing and analyzing antibiotic resistance data and inferring causal relations between use of antibiotics in animal agriculture and negative public health endpoints, decisions concerning the continued and future use of antibiotics in animal agriculture must be, and are being, made on a grand scale (Aarestrup et al, 2001; Aaerestrup et al, 2010). These impact not only the more controversial uses of antibiotics (such as for growth promotion), but also for prophylaxis, metaphylaxis, and even for therapy, particularly when such use conflicts with "critically important antibiotics".

In this paper, I provide several examples from historical, current, and future AR policy, research and surveillance spheres to illustrate these problems and their possible solution.

A historical perspective (1960s to 2005)

Antibiotics are perceived as an essential adjunct to both human and animal health systems worldwide. A range of antimicrobial products have been used to both treat and prevent infectious diseases of animals for over a half-century (Gustafson and Bowen, 1997). Resistance to certain classes of antimicrobials is an inherent feature of some microbes. In other cases, resistance traits can be acquired by microbial species through mutations, and transferred within and among species via sexual and asexual processes. For most bacterial species, it is widely acknowledged that the use of antimicrobials applies pressures that favor the selection and propagation of resistant strains. Indeed, some authors consider increasing resistance to be the inevitable outcome of the use of antimicrobials in both animal agriculture and human health (Levy, 1992). For over forty years, antibiotic resistance has been a serious issue of concern to animal health pharmaceutical regulators in this country and elsewhere. This concern is often illustrated first in the issuance of the Swann Report in the United Kingdom in 1969, followed closely by FDA scrutiny in the US during the 1970's of feed grade antibiotic use in agriculture. Later, outbreaks of multi-drug resistant Salmonella in countries such as Denmark likely helped push the development of resistance surveillance programs such as DANMAP and WHO activities in this area. While the Danish (see Aarestrup, 2010) and subsequently the E.U. ban on antibiotics as growth promoters in 1996 and 2006, respectively, get much of the press, the Swedes had discontinued their use in the mid 1980s. Generally speaking, foodborne outbreaks on a massive scale have tended to result in large scale policy shifts at the national and international levels, be they from organisms with no obvious connection to antibiotic resistance (e.g., *E. coli* O157:H7) or of a multi- or pan-resistant phenotype (e.g., multi-resistant *Salmonella* in the U.K. and Denmark).

Indeed, in recent years, renewed attention has been focused on foodborne diseases. In particular, newly emerging and re-emerging enteric pathogens such as *Escherichia coli* O157:H7, non-typhoid *Salmonella* spp. and *Campylobacter* spp. have captured the interest of public health and veterinary science communities as well as the public at large. Concurrently, global recognition of the increasing resistance of many of these enteric pathogens to presently-available antimicrobials is rapidly developing (WHO, 2011). Many consider the development and spread of multiple antimicrobial resistances in pathogenic bacteria (e.g., *Salmonella* Typhimurium DT104) to be as important a health risk as the emergence of other more widely-recognized infectious diseases. As these "superbugs" continue to develop and acquire more resistance traits, some scientists (Levy 1992) and advocacy groups have begun to predict "doomsday scenarios", whereby the era of antimicrobials may almost be over.

Antibiotic use in agriculture: a call for change

There has been a growing chorus calling for wholesale change in the prescribing practices of antimicrobial agents licensed for both human and animal health (Khachatourians 1998, Witte 1998). Some scientists and politicians point to antimicrobial use in animal agriculture as the primary culprit in promoting resistance of pathogenic organisms

common to both animals and humans. These scientists often lead the call to either: 1) reduce the range of antimicrobial management practices used in animal agriculture (i.e., no growth promotant usages, no subtherapeutic levels in feedstuffs or water), 2) restrict certain classes of antimicrobials to last-line use in human medicine (e.g., 3rd and 4th generation cephalosporins, fluoroquinolones), or 3) remove virtually all uses of antibiotics in animal agriculture except for strictly therapeutic purposes in individually-diagnosed clinical cases (WHO, 2000).

Despite the many uncertainties surrounding the issue, livestock commodity groups have begun to include prudent-use guidelines for antimicrobials in their quality assurance programs. Consumer confidence in the safety of the foods of animal origin is paramount to the long term health and survival of the U.S. beef cattle, poultry and swine industries. Estimating the precise magnitude and importance of antibiotic resistance as a food safety issue in animal agriculture is difficult. Any estimates need to account for the food safety risk uncertainties at each of multiple stages through production, consumption, and (potentially) human disease. Certainly, risk/benefit models must account for the tradeoffs of immediate cattle (and potentially, human) health and growth efficiency benefits from antimicrobial use in the short term, against potentially detrimental impacts on treatment of disease (animal and human) due to resistant organisms.

In general, there are four major uses of antibiotics in food animals (with the nomenclature and taxonomy subject to change depending on the audience). First, and most recognizable, is the use of antibiotics as therapy for clinically ill animals (therapeutic use). Such use can either be on-label, whereby the product is used in an FDA-approved manner, or extra- or off- label where the dose, route, indication, or species of animal treated with the antibiotic many vary from the approved label. It can be via parenteral (injection) or oral dosing. Prophylactic use is generally accepted to mean treatment of individuals or groups of healthy, though 'at-risk', animals at or near therapeutic dose but before they become ill. This differs subtly from metaphylaxis whereby treatment is effected when a certain critical threshold of ill animals during an epidemic is met. Thereafter, all animals in a pen or barn (for example), are treated. Finally, growth promotion is often termed 'subtherapeutic' use of antibiotics though the latter term is often disparaged by clinical pharmacologists. Generally, use of the antibiotics is via feed and is provided to groups of animals to enhance growth rates, feed efficiency, and group uniformity, often through unknown or unclear biological mechanisms. Some also argue that the effects are likely to be through diminishment of subclinical disease and so the term growth promotion is a misnomer. Finally, it is generally accepted that the relative ranking of controversy concerning the use of the products is almost in reverse, with metaphylaxis likely to be slightly less problematic than prophylaxis.

In terms of the critically important antibiotics, as listed by the WHO (WHO, 2011), the top three (see Table 1) are of some concern to U.S. producers since their use spans all four categories as listed above. In general, the products approved in the U.S. as fluoroquinolones are limited to enrofloxacin and this product approval was revoked for use in poultry in 2005. Thus, it is used almost exclusively for therapeutic purposes in animal agriculture. For 3rd and 4th generation cephalosporins the product approved at this time in the U.S. is ceftiofur, available in short-, medium-, and long-acting formulations for injection. These facilitate use as therapeutic, metaphylactic and prophylactic situations under a 'control' label for some indications. This product is currently under review for a possible final ruling to prohibit extra-label use in agriculture. The third product on the top 3 listing is macrolides. The dominant macrolides in use in the U.S. is tylosin, which while available in both parenteral and oral formulations is largely used in feed grade formulations.

Trends in antibiotic resistance: swine versus other agricultural species

A wealth of information on resistance in enteric pathogens, both in the US and around the world, is available through national surveillance programs such as the National Antimicrobial Resistance Monitoring System (NARMS), which is coordinated by three federal agencies: CDC, FDA, and USDA. Indeed, such programs have been used to track the trends of resistance following such large scale interventions as the banning of growth promotants in Denmark in 1996 (Aarestrup et al., 2001). The animal arm of NARMS generally receives isolates (e.g., Salmonella for swine) collected by the USDA-FSIS through routine sampling at slaughter facilities. Until 2007, NARMS also used to receive isolates of

Salmonella from diagnostic laboratories (see Figures 1 and 2).

Several trends are of distinct note for swine producers regarding the NARMS data. First, in terms of evaluating the trends in macrolides resistance (number 3 on the WHO top 3 list for its role in treating campylobacteriosis in children), we have little information since the organism is only tracked in poultry and not in swine. In swine, as in turkeys, the dominant species tends to be *C. coli* rather than *C. jejuni*, and worldwide the former tends to exhibit higher macrolides resistance than the latter. In terms of indicator organisms, recent work in our labs suggests that among indicator species such as enterococci, that virtually all bacteria are resistant to both erythromycin (closely related to tylosin) via the ermB gene and also to tetracyclines (via the tetM gene) (Amachawadi et al, 2011).

In terms of *Salmonella enterica* in swine, information adapted from the NARMS website (USDA, 2011) and the 2008 NARMS Animal Arm Report (USDA, 2010) has been displayed in Figures 1-3. I have included trends in tetracycline resistance to illustrate the point that it is highest in isolates of *Salmonella* from diagnostic laboratories. This shouldn't surprise anyone as these isolates are much more likely to have been derived from animals with prior treatment. The second thing to note is that tetracycline resistance is high, but stable over the past 14 years. It really isn't changing much at all. This is in stark contrast to ceftiofur resistance which is low in swine (compare to broilers and cattle in Figure 3) but rising. This antibiotic class is number 2 on the WHO list. The difference in levels of resistance may well relate to levels of historical use in cattle and broilers versus swine. However, it is just as likely to be lower in swine as a simple function on dominant serovar (see Table 2). It is well recognized that many resistance phenotypes are serovar dependant among *Salmonella* (a trend not seen with generic *E. coli*). Thus, cattle levels have been dominated by the Newport serovar while broilers have been affected by Kentucky and Heidelberg. Among pigs, Derby and Infantis show relatively low levels of resistance to ceftiofur. The resistance levels among *Salmonella* of animal origin to fluoroquinolones remain a relative success in the U.S. at least. In all three hosts (cattle, broilers, pigs) there is virtually no detected resistance using NARMS sampling protocols. This isn't to say the resistance isn't out there, but levels are below the detection limit for NARMS. In other countries, particularly in the developing world, fluoroquinolones resistance is high and climbing among *Salmonella*, *Campylobacter* and other bacteria.

The past five years (2005-2010)

The WHO list of critically important antibiotics

In 2005, a group of infectious disease physicians gathered in Canberra, Australia to develop the criteria for defining the relative importance of classes of antibiotics for human medicine, and to apply those criteria to determine the status of antibiotics of use in either or both of human and animal medicine. The resulting report (see WHO, 2011), which classifies antibiotics as: critically important, very important, or important has been revisited and revised several times since (most recently in Oslo, Norway in June 2011). The listing was controversial from the very start, and it spawned a series of copy-cat lists such as was developed by the world organization for animal health (OIE) as a listing of important antibiotics for animal medicine. The WHO list is less controversial where there are products used solely in animals (e.g., ionophores, bambermycins) or humans (e.g., carbapenems). The controversy arises particularly for classes of antibiotics such as the macrolides and even the tetracyclines. Whatever the problems with the WHO (and OIE, and other national lists) they are here to stay and they do provide a catalyst for discussing the prioritization of antibiotics and their use in both human and veterinary circles.

European ban on antibiotics as growth promoters

The European ban on use of antibiotics as growth promoters took effect on January 1, 2006. This followed other member country leads such as Sweden (mid 1980s) and Denmark (1996). The Danes in particular have been quite vigorous in tracking the effects of the ban on both sales of antibiotics, resistance among bacteria, and production of pigs in particular. Aarestrup and colleagues (Aarestrup et al, 2001; Aarestrup et al, 2010) have published results suggesting: 1) that the ban significantly reduced levels of resistance, particularly among the vancomycin resistant enterococci when avoparcin (never approved in US) and macrolides (tylosin) were removed. Their group also recently published work suggesting that while there was an early increase in treatment of clinically ill pigs, and a slight reduction in pig productivity, that overall the

pig production efficiency has risen in the decade plus since the ban took effect. Of course there are many who disagree with the Danish interpretation of their own data. In particular, in many countries the use of antibiotics in terms of tonnage hasn't changed much since 2006 suggesting that a shift to 'prophylaxis' or other has taken place. Obviously, this country is keeping a very close eye on the European experience as journalists, legislators, FDA commissioners, and others continue to advocate for changes in use of antibiotics in the US.

FDA rule on extra-label use of cephalosporins

Many in the agriculture community were surprised when the Food and Drug Administration (FDA, 2008) issued a 'final rule' effectively banning the extra-label use of cephalosporins in food animals. The resultant backlash has delayed the implementation of this order for almost 3 years now. It was likely initiated by data originating out of Canada concerning in ovo injection of ceftiofur at low doses into eggs at broiler hatcheries. An FDA survey had found that the practice was also employed in the U.S. The data from Canada suggested a marked increase in *Salmonella* Heidelberg resistant to ceftiofur and a precipitous fall off in resistance when the practice was voluntarily ceased. However, since the ruling did not apply simply to that practice, the response to the request for comments was overwhelming and the rule remains pending (as of time of writing).

Emerging pathogens? ***Clostridium difficile,*** *MRSA-ST398 and others...*

The past 5 years have seen a plethora of scientific papers published exploring the presence/prevalence of a variety of different bacteria in retail meats and on-farm. The origin of most of these inquiries seems to relate to identifying non-hospital sources for the expansion of an otherwise hospital-restricted set of nosocomial infections such as *C. difficile* and MRSA. Indeed, we have investigated the prevalence of C. difficile in swine and in humans in a uniquely integrated system in Texas (Norman et al., 2011) and found that both healthy humans and swine harbor the organism within their intestines. However, it is rarely the hyper pathogenic strains that are present, and in the absence of risk factors such as hospital stay, antibiotic use, and others that the organism causes problems. It is much more likely that there is a common environmental source for the anaerobic bacteria's spores that humans and animals alike are exposed to on a day-to-day basis.

Methacillin-resistant *Staphylococcus aureus* (MRSA) has been a scourge of hospitals for three decades. More recently, community acquired infections have led investigators to sample animals and food products and have identified many sequence types in the latter, and among companion animals, but only a restricted type among pigs: ST398. Despite initial fears that the organism could be spread through the food supply, it is generally accepted (EFSA, 2009) that the major risk to humans is through direct contact/colonization at the farm. It is very unclear at this point as to what role antibiotics may play in selecting for the organism.

The future (2012 and beyond)

Existing empirical evidence supports theories suggesting that the use of antimicrobials in both human health and animal agriculture settings leads to the favorable selection (fitness advantage) of resistant strains of bacteria within treated humans/animals or groups of treated humans/animals. However, evidence pertaining to the further transmission of AMR from animals or animal populations to human populations has thus far been circumstantial; based largely on cross-sectional studies and qualitative data from case reports. At this point in time, it remains unclear whether AMR selection pressure in animal agriculture leads either to: 1) long-term maintenance of increased resistance levels in the animal population itself, 2) substantive transmission of resistant bacteria to human populations or, 3) a fitness advantage for any resistant bacteria transmitted to humans leading to long-term maintenance or propagation in the human population.

While there is little doubt that cross-species (i.e., animal to human, human to animal) transmissions can occur, we presently have available little or no quantitative longitudinal data necessary for reliable risk assessments. Rapid technological advances in genetics, microbiology, and biochemistry have recently been integrated with the more field-based disciplines of bacterial population genetics, mathematical biosciences, ecology, evolutionary biology, and epidemiology. By combining these diverse fields, innovative research approaches to antimicrobial resistance in defined human populations have been.

In the meantime, animal agriculture remains responsive the consumer demands, and attuned to public health concerns. Prudent use guidelines as well as alternatives to antibiotics as growth promoters have been developed. In the very near future, studies examining a variety of interventions against antibiotic resistance will be conducted including: exploring potential for plasmid-curing via use of bambermycins, use of products that change lower bowel flora, changes in environments, and use of microminerals (e.g., Cu, Zn) instead of antibiotics. Regarding the latter, we have found that the bacteria themselves adapt quickly to the presence of high levels of copper in feed and as a result can harbor resistance alongside that of antibiotics on mobile genetic elements called plasmids (Amachawadi et al, 2011). Unfortunately, this means that bacterial adaptation to alternatives to antibiotics can still co-select for resistance even when the antibiotics are not being used. Despite some setbacks, pursuit of alternatives remains a worthwhile goal and there are likely to be some successes down the line that focus more on changing the host and environmental ecology to favor susceptible over resistant strains.

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Tables

Table 1: World Health Organization (WHO) listing of top 3 critically important antibiotics (CIA) and their rationale for inclusion. Adapted from 2nd revision of the WHO listing (WHO, 2011).

Antibiotic class (*example of veterinary drug*)	Comments on food animal use and implications	Specific rationale for inclusion
Quinolones (***enrofloxacin***)	**Quinolones** are widely used in food animal production and are known to select for quinolone-resistant *Salmonella* spp. in animals. At the same time, quinolones are one of few available therapies for serious Salmonella infections, particularly in adults. Given the high incidence of human disease due to *Salmonella* spp., the absolute number of serious cases is substantial.	High absolute number of people affected by all diseases for which the antimicrobial is the sole/one of few therapies available. High frequency of any use of the antimicrobial in human medicine regardless of indication given that usage for any reason may result in selection pressure for resistance. Transmission of *Campylobacter* spp. and Enterobacteriaceae including *E. coli* and *Salmonella* spp. from non-human sources
Cephalosporins (3rd and 4th generation) (***ceftiofur***)	**3rd and 4th generation cephalosporins** are widely used in food animal production and are known to select for cephalosporin-resistant *Salmonella* spp. in animals. At the same time, 3rd and 4th generation cephalosporins are one of few available therapies for serious Salmonella infections, particularly in children. Given the high incidence of human disease due to *Salmonella* spp., the absolute number of serious cases is substantial.	High absolute number of people affected by all diseases for which the antimicrobial is the sole/one of few therapies available. High frequency of any use of the antimicrobial in human medicine regardless of indication given that usage for any reason may result in selection pressure for resistance. Transmission of *Campylobacter* spp. and Enterobacteriaceae including *E. coli* and *Salmonella* spp. from non-human sources
Macrolides and ketolides (***tylosin***)	**Macrolides** are widely used in food animal production and are known to select for macrolide-resistant *Campylobacter* spp. in animals. At the same time, macrolides are one of few available therapies for serious campylobacter infections, particularly in children, in whom quinolones are not recommended for treatment. Given the high incidence of human disease due to *Campylobacter* spp., the absolute number of serious cases is substantial.	High absolute number of people affected by all diseases for which the antimicrobial is the sole/one of few therapies available. High frequency of any use of the antimicrobial in human medicine regardless of indication given that usage for any reason may result in selection pressure for resistance. Transmission of *Campylobacter* spp. from non-human sources.

Table 2: Top ten *Salmonella enterica* serovars isolated from cattle, broilers and pigs at slaughter in 2008. Adapted from NARMS 2008 report (USDA, 2011).

Cattle	**No.**	**%**	**Broiler**	**No.**	**%**	**Pigs**	**No.**	**%**
Montevideo	104	23.5	Kentucky*	219	35.1	Derby	25	22.5
Newport*	53	12.0	Enteriditis	116	18.6	Infantis	15	13.5
Dublin*	31	7.0	Heidelberg*	94	15.1	Agona*	6	5.4
Anatum	27	6.1	Typhimurium v 5-*	39	6.3	London	6	5.4
Cerro	27	6.1	Typhimurium*	31	5.0	Saintpaul	6	5.4
Typhimurium*	25	5.6	I 4,[5],12:i:-	23	3.7	Typhimurium v 5-	6	5.4
Kentucky	22	5.0	Infantis	14	2.2	Anatum*	5	4.5
Muenster	18	4.1	Montevideo	13	2.1	Johannesburg	5	4.5
Agona*	17	3.8	Schwarzengrund	7	1.1	Ohio	4	3.6
Representing:	**324**	**73.1**	**Representing:**	**556**	**89.1**	**Representing:**	**78**	**70.3**
Out of:	**443**	**100**	**Out of:**	**624**	**100**	**Out of:**	**111**	**100**

*Moderate to strong association with ceftiofur resistance

Figures

Figure 1: Trend of tetracycline resistance among *Salmonella enterica* isolated from slaughter samples (1998 – 2010) collected by the USDA Food Safety and Inspection Service (FSIS) (grey line, grey circles) and US diagnostic laboratories (1998-2007) (black line, black circles) and submitted to the National Antimicrobial Resistance Monitoring System (NARMS) for phenotypic analysis. Adapted from NARMS data (USDA, 2011).

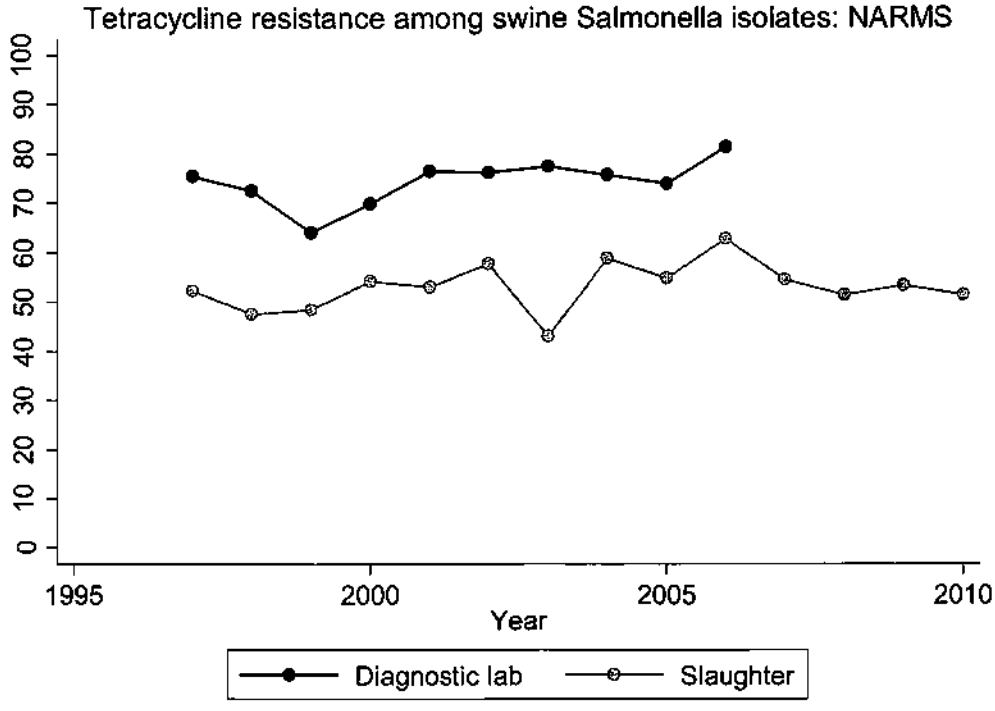


Figure 2: Trend of ceftiofur resistance among *Salmonella enterica* isolated from slaughter samples (1998 – 2010) collected by the USDA Food Safety and Inspection Service (FSIS) (grey line, grey circles) and US diagnostic laboratories (1998-2007) (black line, black circles) and submitted to the National Antimicrobial Resistance Monitoring System (NARMS) for phenotypic analysis. Adapted from NARMS data (USDA, 2011).

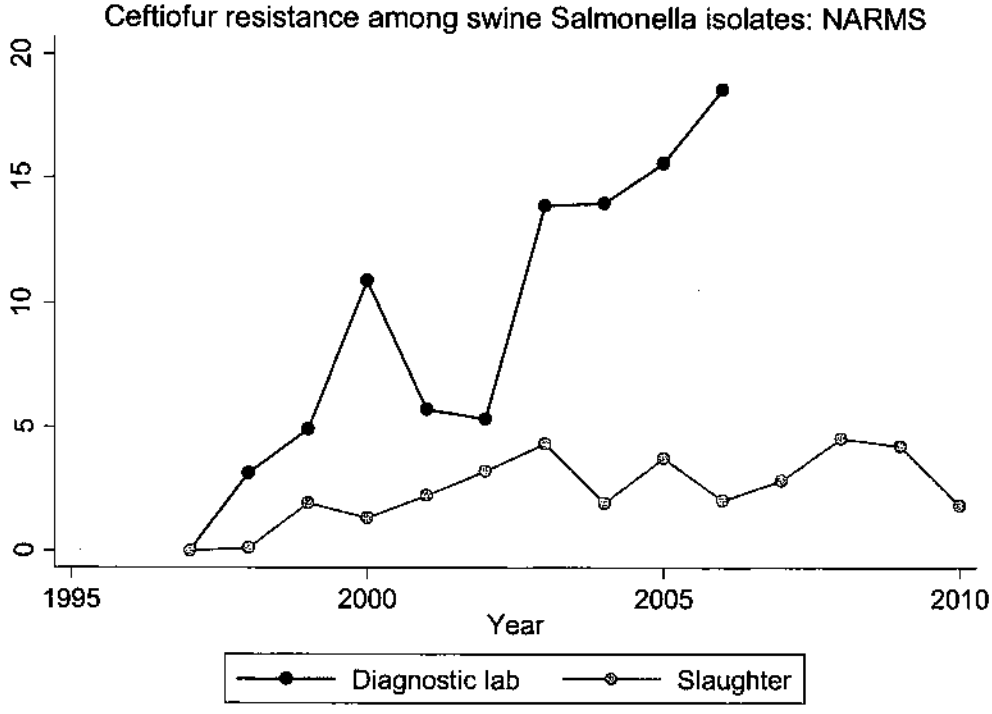
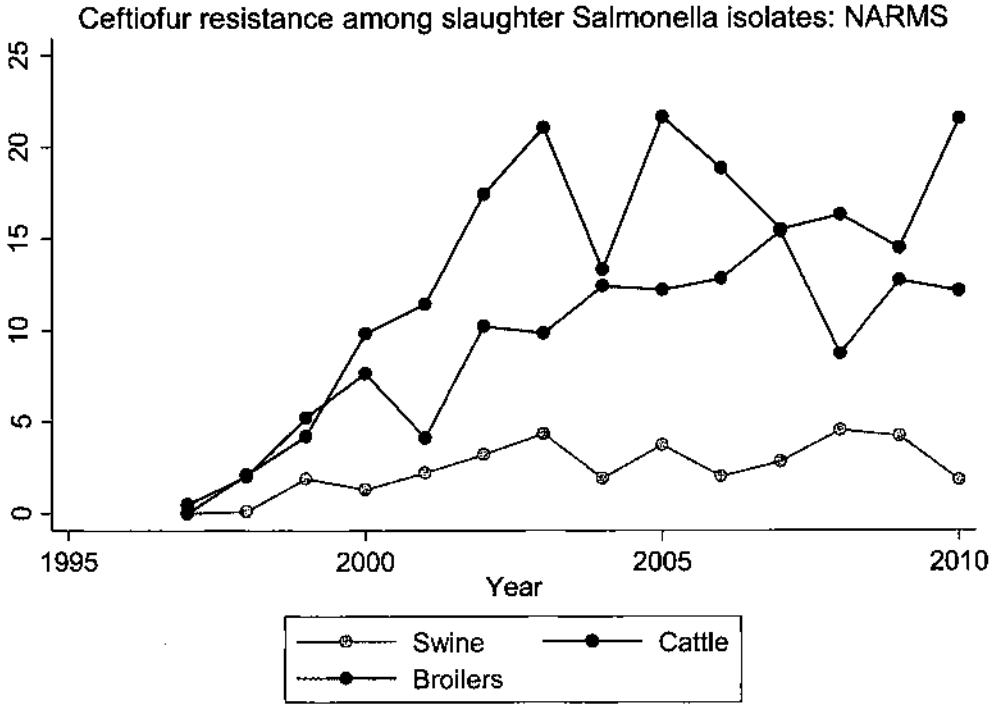


Figure 3: Trend of ceftiofur resistance among *Salmonella enterica* isolated from slaughter samples (1998 – 2010) collected by the USDA Food Safety and Inspection Service (FSIS) for cattle (black line, black circles: cannot discern beef from dairy), broilers (dark grey line, dark grey circles) and pigs (light grey line, light grey circles) and submitted to the National Antimicrobial Resistance Monitoring System (NARMS) for phenotypic analysis. Adapted from NARMS data (USDA, 2011).



Zinc, More than a Feed Ingredient— what do pigs really need?

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Summary

Zinc is required by the pig, but historical requirements in using modern technology with the modern genotype suggest that dietary requirement levels may be incorrect. Research shows that healthy pigs of high lean genetics and from sows fed nutritionally adequate diets do not need the amount of Zn recommended by NRC (1998). Additionally, organic Zn (Bioplex Zn) appears to stimulate a greater amount of metallothionein (Mt) in the duodenum for the absorption of Zn than inorganic Zn. Body compositional studies clearly show that different genotypes do not manage Zn similarly as pigs of the past. Hence, requirements need to consider nutritional history, age, physiological state and genotype.

Introduction

Healthy animals that have met their nutrient needs can increase their efficiency of production because they can use their own biology to resist disease while maximizing their genetic potential for reproduction, feed efficiency, gain and other important production parameters. Today's advancing scientific techniques are uncovering new roles for trace elements that in the past have been masked by old dogmas, poor scientific designs and the lack of appropriate technologies. Twenty years ago, E. R. Miller (1991) never mentioned in his book how zinc (Zn) absorption occurred, but today's cutting edge researchers study valence changes, transport proteins, receptors, binding proteins, regulatory proteins, and storage proteins to examine how the body's needs for Zn are met. Zinc research is no longer just feed'em and weigh'em and find out how much Zn is in tissues!

Hambidge (2010) noted that factors that affect usefulness of an element to the animal are, in reality, triggering or the result of regulatory responses designed to maintain optimal homeostasis for the health of the animal. Hence, homeostasis for the element and ultimately the organism are really what is needed for the animal's metabolic needs. A "required amount" for all is out-dated. Today, we need to consider genetic and acquired differences at the cellular and sub-cellular level. Hinson's work at Purdue (2005) with several genotypes clearly shows this.

Biochemistry of Zinc

Zinc most likely exists as a divalent ion (Zn^{2+}), and in the body it is likely complexed with amino acids to maintain the structure of enzymes or be a part of the reaction. Besides enzyme function, Zn is involved in transcription as Zn-fingers, and in intra- and intercellular signals to the nucleus.

The duodenum is the major site of Zn absorption into the enterocyte by a carrier-mediated process. The absorption of Zn is thought to be enhanced by substances that are ligands. Usually Zn binds to the S or N in amino acids such as cysteine, histidine, glutamine, and glycine. It appears that the binding to ligands helps to maintain the solubility of Zn in the GI tract. It is not clear if Zn bound to amino acids is absorbed via amino acid transporters. The hydrolysis of dietary Zn from amino acids, nucleic

acids, etc., has to occur via the digestive processes in the stomach and small intestine for Zn absorption to occur. Thus, Zn is **not** bound to amino acids, phytate, etc. when the carrier protein, ZIP4, moves Zn across the brush border. The role of metallothionein (Mt) appears to be important in holding the free Zn in the mucosa of the duodenum so that it can be picked up by a carrier protein. The DMT1 protein can carry Zn, but it is not thought to be as important as ZIP4. Additionally, when pharmacological Zn is fed, Zn overrides the controls of the enterocyte and is absorbed by passive diffusion and paracellular absorption.

Zinc is primarily transported in the blood by albumin, but transferrin, α-2 macroglobin and immuno-globin G (IgG), histidine and cysteine can also transport Zn. The uptake or release of Zn by cells involves ZIP carriers 1, 2, 4, 6, 7, 8, and 14 and the ZnT family. The ZIP 14 protein transports Zn into the liver cells and is up-regulated during an acute phase reaction (stress, illness, etc.) so that circulating Zn is decreased. Two important Zn exporters from the ZnT family are ZNT1 located on the plasma membrane especially of the small intestine and kidney and ZnT4 located on the plasma membrane of the mammary gland and brain. ZnT2 assists in Zn uptake into the intestine, testis and kidney, and ZnT3 is involved in Zn uptake in neurons and the testis. Additionally, ZIP3, regulated by prolactin, is involved in the uptake of Zn by the mammary gland (Kelleher and Lönnerdal, 2005). Our laboratory (Martinez-Montemayer et al., 2008) reported that ZnT1 was up-regulated in the duodenum of pigs fed pharmacological Zn.

Organic vs. Inorganic Zn in Nursery Pigs

To determine if Zn source influenced performance and Zn metabolism in nursery pigs, 500 crossbred [(Yorkshire X Landrace) X PIC (line 289)] pigs (18 to 20 days of age) were fed diets with 25, 50, 75, or 100 mg/kg added Zn from either an organic Zn source (Bioplex Zn) or an inorganic source (Zn sulfate). Additionally, the study included a negative control diet with no added Zn (31.9 ppm innate Zn in the diet) and a 50 ppm Zn diet with Zn provided as 25 mg/kg organic and 25 mg/kg inorganic Zn. In agreement with previous work (Martin et al., 2011), pigs in this study fed unsupplemented complex nursery diet (31.9 ppm Zn) did not gain as fast or consume as much feed ($P \leq 0.05$) in this 35 d nursery trial (Table 1). There was a quadratic response ($P \leq 0.05$) to organic Zn supplementation for average daily gain (ADG) and daily feed intake (FI).

At 10 d post weaning, the liver weight and hepatic Zn concentration were not different, but there was a greater amount of Zn in the liver of pigs who were fed dietary Zn (Table 2). However, at 35 d post-weaning, liver weight increased as the amount of organic Zn in the diet increased ($P \leq 0.05$), and the livers of animals fed Zn supplemented diets contained more Zn than pigs fed the basal or unsupplemented diet ($P \leq 0.05$). For both Zn sources, hepatic Zn increased as dietary Zn increased ($P \leq 0.05$), but pigs fed both sources of Zn in their diet had lower hepatic Zn concentrations than pigs fed the same amount of Zn from either organic or inorganic Zn sources.

However, when metallothionein (Mt), a protein that binds many cations including Zn, was measured in the liver, duodenum and jejunum, the response to the two Zn sources was not the same. For liver and duodenal Mt, there was both a level and a source response ($P \leq 0.05$) with the organic Zn response being greater with 25 and 50 ppm additional Zn in the liver (Table 3) and with 25, 50 and 100 ppm in the duodenum. Regardless of Zn source, jejunal Mt was lower at 0, 10 and 35 d after supplementation compared with duodenal Mt. This is an expected difference since the jejunum has only a minor role in Zn absorption compared with the duodenum. There was a response to Zn level for both sources of Zn in this tissue ($P \leq 0.05$).

Influence of Genotype on Zn Deposition

Work from Purdue University (Hinson, 2005) reported that a low nutrient excretion diet did not decrease the Zn in the whole empty body mineral mass in PIC and Danbred genotypes. However, there was a treatment X sex interaction for Ausgene genetics, and sex approached significance ($P < 0.06$) for Genetiporc pigs. Work from The Ohio State University reported that the empty body Zn concentration increased linearly with increasing weight, and high-lean pigs had a higher concentrations of Zn than low-lean pigs from 20 to 125 kg body weight, but was exacerbated during the finisher period when more muscle is deposited in

the modern pig (Wiseman et al., 2009). This higher Zn content was largely in the loin and ham muscles, but not in the remaining body tissue (Wiseman and Mahan, 2010). These compositional differences confirm the hypothesis of Clawson et al. (1991) and indicate that prediction of nutrient needs cannot be done by body weight alone, but that genetics must be considered.

Conclusion

Nursery pigs do not manage organic and inorganic Zn in the same manner. Organic Zn (Bioplex Zn) initiates absorption of Zn by increasing the amount of Mt in the duodenum where Zn is absorbed. The Mt has the potential to hold the Zn for binding by the carrier protein for entry into the enterocyte. As expected because of its role in Zn absorption, the amount of Mt protein in the duodenum is two-fold that in the jejunum. Even with the modern pig, the amount of Zn required for high-lean genotype nursery pigs is below what is currently recommended (NRC, 1998).

Also, because of compositional differences; genotype, not just age and physiological state, should be considered when determining nutrient needs.

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Table 1. Effect of dietary organic (O) and inorganic (I) Zn sources at various dietary levels on pig post weaning performances.

	Zn source:	Basal	Organic Zn (O), mg/kg				Inorganic (I), mg/kg				Comb.	
	Zn level:	0	25	50	75	100	25	50	75	100	25 + 25	SEM
	Treatment no.:	1	2	3	4	5	6	7	8	9	10	
Item	No. replicates[1]:	10	10	10	10	10	10	10	10	10	10	-
Weight, kg d 35		18.9	19.3	19.6	19.8	19.5	19.6	19.1	19.2	19.5	19.6	0.6[2,3]
Daily gain, g 0 to 35 d		379	389	398	397	367	389	378	385	396	389	15[2,3]
Daily feed, g 0 to 35 d		561	582	590	608	568	595	560	579	591	578	22
Gain:feed ratio, g/kg 0 to 35 d		676	668	675	653	646	654	675	665	670	673	19

[1]Each pen contained 5 pigs (n = 50 pigs/treatment).
[2]Treatment 1 vs. treatment 2 to 10, $P < 0.05$.
[3]Regression analysis of organic treatment 1, 2, 3, 4, 5 (quadratic, $P < 0.05$).

Table 2. Interaction effect of dietary Zn sources and levels on liver micromineral concentration (10 and 35 d post weaning).

	Zn source:	Basal	Organic Zn (O), mg/kg				Inorganic (I), mg/kg				Comb.[1]	
	Zn level:	0	25	50	75	100	25	50	75	100	25 + 25	SEM
Item	Treatment no.:	1	2	3	4	5	6	7	8	9	10	
10 d[1]												
Liver wt., g		129	154	159	156	157	169	125	156	151	148	18
Liver DM, %		26.0	26.4	26.8	27.1	26.7	26.6	25.8	27.1	26.7	26.8	0.5
Liver Zn, µg/g		45.5	62.4	46.8	59.4	50.0	51.5	65.2	55.4	44.0	66.9	8.6
Liver Zn content, mg		4.61	7.66	7.40	8.43	6.83	6.40	7.62	10.50	7.31	6.09	1.17[3,4]
35 d[2]												
Liver wt., g		651	700	720	755	793	785	760	740	704	764	46[5]
Liver DM, %		28.1	28.0	28.8	28.7	28.7	28.9	28.1	27.8	28.8	27.3	0.9
Liver Zn, µg/g		29.9	33.0	48.1	63.4	63.6	33.5	43.0	56.8	64.9	41.4	5.0[5,7,8,9]
Liver Zn content, mg		19.1	23.0	36.7	43.9	58.2	27.8	33.2	44.0	49.9	36.6	7.5[3,5,8]

[1]n = 6; Comb. = Combination of organic and inorganic sources.
[2]n = 8.
[3]Treatment 1 vs. treatment 2 to 9, $P < 0.05$.
[4]Regression analysis of inorganic treatments 1, 6, 7, 8, 9 (quadratic $P < 0.05$).
[5]Regression analysis of inorganic treatments 1, 6, 7, 8, 9 (linear, $P < 0.01$).
[6]Regression analysis of organic treatments 1, 2, 3, 4, 5 (linear, $P < 0.05$)
[7]Treatment 1 vs. treatment 2 to 9, $P < 0.01$.
[7]Regression analysis of organic treatments 1, 2, 3, 4, 5 (linear, $P < 0.01$).
[8]Treatment 10 vs. treatments 3 and 7, $P < 0.01$.

Table 3. Effect of dietary source and level of microminerals on hepatic enzyme activities.[1,2]

	Zn source:	Basal	Organic Zn (O), mg/kg				Inorganic (I), mg/kg				Comb.	
	Zn level:	0	25	50	75	100	25	50	75	100	25 + 25	SEM
Item	Treatment no.:	1	2	3	4	5	6	7	8	9	10	
Liver Mt, μg/g tissue, wet[3,4]												
d 0		1,116	-	-	-	-	-	-	-	-	-	-
d 10		333	676	569	563	447	359	353	572	497	574	117
d 35		79	109	265	725	611	109	312	614	539	236	99
Duodenum Mt, μg/g tissue, wet[3,6]												
d 0		65.3	-	-	-	-	-	-	-	-	-	-
d 10		22.2	32.9	35.0	58.7	40.8	32.9	35.5	35.4	35.6	37.0	5.9
d 35		30.2	30.5	32.0	40.7	40.6	33.3	34.6	37.3	50.1	33.7	3.2
Jejunum Mt, μg/g tissue, wet[5]												
d 0		17.9	-	-	-	-	-	-	-	-	-	-
d 10		16.6	18.1	15.4	18.7	19.2	17.2	16.9	19.3	20.1	18.2	1.9
d 35		16.3	15.6	16.8	16.3	18.2	16.2	15.8	16.8	19.5	13.7	1.2

[1]The 0 and 10 d values each represent 6 observations.
[2]The 35 d values each represent 8 observations.
[3]Dietary Zn level response (linear, $P < 0.01$).
[4]Dietary source response (linear, $P < 0.05$).
[5]Dietary Zn level response (linear, $P < 0.06$).
[6]Dietary source response ($P < 0.05$).

Considerations in the aggressive use of co-products for swine feeding

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Summary

The growing competition for feedstuffs for food, feed and fuel has forced the feed industry to search for alternative feedstuffs. Moreover recently feedstuff prices have been volatile. Co-products are an often attractive alternative source, although availability can vary in different regions. However, they contain less starch and have higher NSP and fiber contents. Furthermore, the contaminants are more concentrated than in the original feedstuff. The large variation in nutritional quality of these products requires special attention of feed formulators. More accurate table values, correction factors for variation in quality and gate control are essential for an optimal use of these products.

The different nutrient composition also demands stronger restrictions in the formulation for aspects that are not necessary in simple corn soy diets.

The high content of potentially fermentable carbohydrates along with an often lower amino acid digestibility also enhances health risks especially in antibiotic free conditions and during (sub)clinical gastro-intestinal disturbances.

Introduction

The growing world population and a higher average income in developing countries results in an increased demand for animal protein and therefore livestock production and the production of first generation biofuels have resulted in an accelerated usage of feedstuffs. In the last decade the global stocks of cereals have been gradually reduced. This has resulted in structural higher feedstuff prices and more volatility in the feedstuff market. The livestock industry will have to compete with the biofuel industry for feedstuffs. This will become more difficult as energy prices increase and biofuel production becomes more attractive. Feed producers will be forced to look for alternatives for traditional feedstuffs like cereals and oil seed meal, in order to be able to produce feeds competitive and profitable. These alternatives are often co-products of other industries like the biofuel industry or food processors.

For an optimal utilization of these co-products, the industry has to take into account the availability of the co-products, their nutritional value, the variation in quality, their potential negative effects on animal health, feed and food safety and their effect on the quality of animal products. In this paper these aspects of the use of co products will be discussed based on the experience in western Europe with a focus on the economic aspects.

Types of co-products

In the world many different co-products are available, the can originate from the food industry, are co-products of the production of vegetable oils, slaughter plants, the biofuel industry or other sources. In general, for industries producing co-products the (nutritional) quality and consistency in quality of these co-products is not a primary concern. Consequently they are therefore very variable in chemical composition and mostly low in starch. Products derived from plant origin are often rich in fiber and non starch polysaccharides (NSP's). Due

to the production process minerals and contaminants like mycotoxins are often concentrated in the co-products.

Protein rich by-products are susceptible to heat damage when the drying process is too intensive, lowering amino acid digestibility in general and that of lysine specifically.

Evaluation of co-products

Optimal use of any feedstuff in feed formulation and producing animal feeds with a consistent predictable technical performance requires reliable nutrient values, which reflect the physiological metabolism of the nutrients. For that reason a Net Energy–system is preferred for the energy content, Standardized Ileal Digestibility for amino acids and retainable Phosphorus for P. The more accurate these contents can be predicted, the more consistent diets including co-products can be formulated. Since the energy content of a feed is the most costly factor determining the feed price, the focus should be on the energy evaluation. Moreover the (Net) energy content of the feed has a major impact on the feed conversion ration (FCR) and therefore the feed cost per kg gain. Especially for co-products some aspects are important.

Often the NE-content of co-products is lower than the feedstuffs they are originating from since starch and/or fat has been removed. Incorporating co-products in feed formulation will therefore often result in a lower NE-content of the feed unless the usage of high energy feedstuffs (like fats & oils) is increased. In order to produce feeds with a consistent technical performance feeds need to be formulated on a fixed NE-content and a fixed NE/SID amino acid ratio.

Even more important than the absolute NE-value of a feedstuff is the correct relative value of one feedstuff compared to another. In least cost formulation programs this determines the amount of a feedstuff that is incorporated in the formulation at a given price. Therefore, feedstuffs should be evaluated as much as possible in comparative digestion experiments, that is under the same conditions, with the same basal diet, at the same time and institution. Despite the fact that in different studies the same protocol may be used, different nutrient digestibility coefficients for the same feedstuff between experiments may be obtained. Large digestion experiments with a considerable amount of feedstuffs, variable qualities of the same feedstuff and control feedstuffs between trials will make it possible to make equations so that the nutrient value of each feedstuff can be estimating from the chemical composition.

The experiments should be performed at feed intake levels that the animals consume in practice. High feed intakes result in lower digestibility coefficients. This reduction is not the same for all nutrients. The digestibility of the starch is hardly affected by feed intake level, whereas the digestibility of the fibrous fractions can be reduced considerable at higher feeding levels. This is especially important for the evaluation of co-products. If these are determined at low feed intake levels their nutritional value will be overestimated.

If one feeds pelleted diets, the feedstuffs should be evaluated in pelleted feeds. In general pelleting has a positive effect on the digestibility of the organic matter, and especially on the fiber and fat fractions. Pelleting can therefore significantly increase the value of co-products from plant oil extraction like sunflower and rapeseed meal.

The effect of physiological stage or age of the animal has also a different effect on the digestibility of various nutrients. The digestibility of starch is hardly affected by the age of the animal, whereas the digestibility of the fiber fraction and in a lesser extent that of protein and fat increases as the animal matures. Therefore co-products have normally the highest shadow prices in feeds for sows followed by growing/finishing pigs and the lowest in piglet diets.

How to deal with the variation in quality?

Co-products are variable by nature. One should therefore work with flexible instead of fixed matrix values. The variation is caused by the fact that the normal variation in chemical composition are compounded in co-products and the different production processes from which these products originate. Pre-processing treatment, removal of fractions (bran, germs, oil, starch or gluten), heat application during processing, use of enzymes, addition of processing aids and drying conditions of the co-product all affect the nutritional quality of the co-product to a certain extent. Knowledge of the under lying production process of the co-product is essential and single sourcing is preferable . However, even in this ideal situations, the within plant variation

in quality can be considerable. In practice the producer and the production process is not known. Therefore, a gate control at the moment that a new batch of the feedstuff is received in which at least the chemical composition (NIR) is monitored will be essential. It is essential that the analyzed nutrient values can be converted to matrix values. In Figure 1 the relation between the fat content of corn DDGS and the NE-value is shown.

The relation shown is a very simple relation which can be used due to the fact that fat is a dominant factor for the energy content. However in most products the variation in fat content is not as large and the effect of the chemical composition on the energy value has been determined in a more complex way. The net energy content is calculated based on the amount of digestible nutrients

NE (MJ/kg DM) = 10.8 * digestible crude protein + 36.1 * digestible crude fat+ 13.7 * starch+ 12.4 * ileal digestible sugars + 9.6 * fermentable carbohydrates

Not only is the nutrient content variable but the digestibility of the nutrients also relates to the quality of the feedstuff. For example, for wheat DDGS we found the following relations between the digestibility of protein and fat:

dig. protein = 0.83 x crude protein – 0.28 x fibre

dig. fat = 0.94 x crude fat – 0.0083 x fibre

This emphasizes that matrix values should be (re)calculated for each batch of co-product and that the usage of fixed table values will lead to variable results in practice.

Other aspects causing nutritional variation in feedstuffs are anti-nutritional factors and undesired substances like mycotoxins. Often quick screening methods are not sufficient to determine the exact level of contamination on a routine basis, while GLC-analyses are expensive and finished by the time the product has been used.

Insufficient nutritional information about the feedstuff has a cost enhancing effect. Either in the formulation larger safety margins for nutrients will be have to be used (off setting possible cost savings) or the technical performance of the animals is negatively affected.

Restrictions in least cost formulations

An aggressive use of co-products in the feed formulation requires more restrictions than one normally should do in simple diets. Factors that earlier do not seem to be important or were empirically known, will have to be considered. Not only for optimal production but also to meet requirements regarding to meat quality, animal health and /or welfare or the environment.

Examples are:

- Limitations in the U/S (unsaturated/ saturated fatty acid) -ratio to prevent soft fat or to optimize fat digestibility.
- More precise definition of the optimal (SID) amino acid profile for maintenance, growth and lactation and the maximum usage of synthetic amino acids.
- Limitations on the non starch polysaccharide content of the feed.
- Limitations on the maximum crude protein content in the feed or the indigestible crude protein content per species.
- P content and availability of the diet.

One should realize that every additional restriction will potentially have a price increasing effect.

What are the major challenges using co-products ?

The major challenge using co-products will be with the usage under suboptimal animal health conditions. Especially, with the use of byproducts the diets contain less starch, more NSP's, and have a decreased protein, fiber and/or fat digestibility. When a gastro-intestinal disorder causes a reduction in the absorption capacity in the small intestine, digestion of fat and protein will be reduced more than that of starch which is hardly affected. Due to the availability of NSP's as an energy source and indigestible crude protein as a nitrogen source microbial growth is stimulated in the large intestine and the microbial population will have a tendency to shift towards more potentially pathogenic bacteria. A high fermentation rate will therefore increase the risk for diarrhea and a reduction in feed intake.

At Schothorst Feed Research we have introduced the terms fermentable fiber and indigestible crude protein in order to be able to quantify the amount of potentially fermentable material in a feed and to be able to use it as a nutrient restriction during feed formulation.

Overheating of protein due to severe drying conditions of co-products like DDGS or the processing of Meat and Bone meal or the extraction of plant oils oil seeds decreases ileal amino acid digestibility. Well known is the occurrence of Maillard reactions between lysine and reducing sugars however over all amino acid digestion is decreased when the bioavailability of lysine is reduced. This ileal undigested protein becomes a nitrogen source for microbes negatively influencing gut health but also decreasing the barn climate due to high ammonium levels. For instance per 1% inclusion of maize DDGS the crude protein content of a typical grower/finisher swine feed is increased with 0.1% and the amount of indigestible protein coming from maize DDGS with 0.03 %.

Fermentable carbohydrates are those carbohydrates that are not hydrolyzed in the small intestine and can be fermented in the distal ileum, ceacal and colon. The fermentable carbohydrate fraction is a biological parameter and varies depending the age and health of the animal. In our recommendations for feed formulation for fattening swine we used data obtained with healthy pigs in the weight range from 50 till 85 kg.

Fermentable carbohydrate restrictions are of particular importance in situations in which the use of antibiotics as growth promotants are banned in animal feeds as presently in the EU and parts of Asia. In a Schothorst experiment we have studied in swine diets the effect of on the amount of fermentable carbohydrates varying from 120 till 210 g/kg. The diets were not supplemented with antibiotics. The results showed that the fermentable carbohydrate content of the feed had a dose dependant negative effect on the feed conversion ratio and the average daily gain..

Another aspect than should be considered is the starch content in the diet. Normally, starch is sufficiently present in the diet. However starch does not only have a function as carrier of glucogenic energy but the resorbed glucose also has a function as metabolite that affects hormonal regulation. For example, insulin not only stimulates the transport of glucose into cells but also of amino acids. Starch levels that are too low may cause a lower efficiency of protein deposition.

Probably the greatest challenge is to develop an accurate and rapid method to determine the heat damage in protein rich co-products. Especially those feedstuffs that have been heat treated during the process are sensitive. Since the economical value of most of these co-products is limited, the processing of the co-products is more focused on high output (volume) than the quality of it. This increases the risk for exposure to too high temperatures and/or for too long. This is applicable for meat and bone meal, fish meal, milk proteins but also for by-products from the starch industry, production of oil seed meals and DDGS.

Although this is a problem occurring with co-products, its is not limited to these feedstuffs. Also too intensive drying of cereals may cause protein damage and/or resistant starch.

Conclusions:

1. Large amounts of co-products can be used in swine feeds. This has the potential to reduce feed costs but also to give added value to these products over f.i. use as biomass. Due to the nature of co-products, these diets will contain relatively less starch, more NSP's, fiber and fat than the products they originate from.
2. In order to be able to produce feeds with a predictable and consistent performance for swine, one should use accurate nutrient table values (specifically Net Energy and SID amino acids). These should be estimated from equations based on the actual chemical composition (Net Energy) to correct for the variation in quality.
3. Co-products should nutritionally be evaluated in comparative digestion experiments under the same conditions as they are fed to the animals: intake level, form of the feed and age/weight should be practice alike. From these experiments equations as mentioned in 2. should be derived by studying several co-products varying in quality in relation to the original feedstuffs.
4. The use of a wider range of feedstuffs also requires more restrictions in the formulation of feeds.
5. Mature animals with a relatively low intake can utilize co-products better than young animals with high feed intakes. Therefore, higher levels

of co-products can be incorporated in feeds for gestating sows but the usage is limited in piglet feeds.

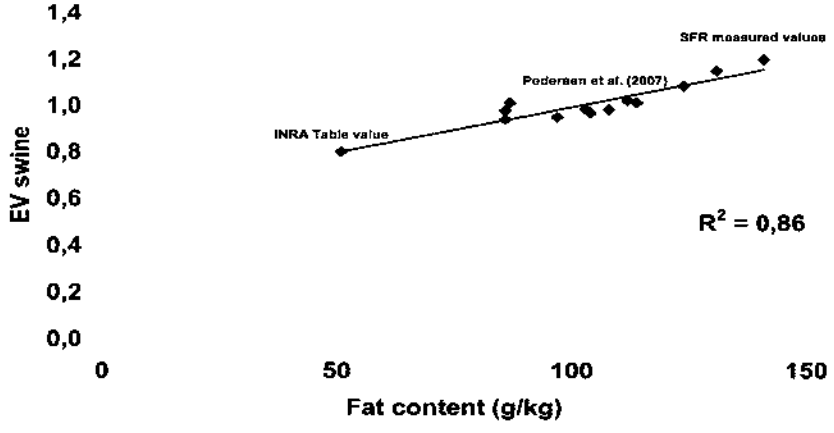
6. The major challenges are:

- To deal with the high NSP content, which enhances the severity of gastro-intestinal disorders.
- Estimating ileal digestibility of amino acids and limiting the amount of indigestible crude protein for gut health and environmental reasons.
- To estimate the nutritional value (NE-content) of the co-product and especially the amount and effect of heat damage
- Starch requirements need to be considered in feed formulation.

Most important:

- Quick screening and monitoring quality at receiving or gate control
- Analysis for chemical composition and undesirable substances in conjunction with equations for correction feedstuff table values.
- Maintenance of the feedstuff tables
- Single sourcing and product knowledge. Contact with and an open relation with the producers of the co-product are paramount.

Figure 1. The relation between fat content in corn DDGS and its NE-value (1 EV= 8.8 MJ NE)



Standardized Total Tract Digestibility (STTD) of Phosphorus

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SUMMARY

The standardized total tract digestibility of P can be calculated by correcting values for the apparent total tract digestibility P for the basal endogenous losses of P. Basal endogenous losses of P have been determined in a number of experiments and average approximately 200 mg per kg dry matter intake. Unlike values for the apparent total tract digestibility of P, values for the standardized total tract digestibility of P, are not dependent on the inclusion rate of P in the diet and these values are, therefore, believed to be additive in mixed diets. The fecal excretion of P can also be calculated from these values, which will make it possible to predict P-excretion from animals fed diets that were formulated on the basis of standardized total tract digestibility of P. The quantity of standardized total tract digestible P will most accurately reflect the quantities of P in mixed diets that pigs can utilize and practical diet formulation should, therefore, be based on values for the standardized total tract digestibility of P.

INTRODUCTION

The quantity of P that is available to pigs in a feed ingredient is often determined by the relative bioavailability of P in the ingredient. To determine this value, several diets containing graded levels of the ingredient need to be formulated, animals are fed the diets for 4 to 6 weeks and then sacrificed, bones are extracted from the front feet, and the P in the bones is determined. This procedure is relatively expensive and labor intensive, and results obtained for individual feed ingredients are not always additive in mixed diets. As an alternative, the apparent total tract digestibility (**ATTD**) of P in a feed ingredient may be determined using a diet that contains this ingredient as the sole source of P. The diet is fed to individually housed pigs and the feces from the pigs that are fed the diet are collected and analyzed for P. Pigs are not sacrificed, and only one diet per ingredient is needed. This procedure is, therefore, less expensive and much faster than the procedure used to determine the relative bioavailability of P. It has, however, been demonstrated that the values for the ATTD of P that are obtained depend on the concentration of P in the diet (Fan et al., 2001). The reason for this observation is that the endogenous losses of P contribute a greater proportion of total P output if P is included in diets at low inclusion rates than if P is included at a greater concentration. To solve this problem, values for the ATTD of P may be corrected for the endogenous losses, which will result in calculation of values for the digestibility of P that are independent of the concentration of P in the diet. These values are, therefore, believed to be additive among feed ingredients when mixed into a common diet.

DETERMINATION OF ENDOGENOUS LOSSES

There are 2 forms of endogenous losses that may be used to correct values for the ATTD of P. These are the basal endogenous losses and the total endogenous losses. Total endogenous losses may be determined using the regression procedure (Fan et al., 2001), which requires that graded levels of a feed ingredient are fed to animals, thus providing

graded levels of P intake. By regressing P intake for each diet on the output of P and extrapolating this regression line back to zero P intake, the Y intercept of the regression line is considered the total endogenous loss of P. Alternatively, the total endogenous loss of P may also be determined using diets containing radioactive labeled P (von Lantzsch et al., 1965). However, there appears to be great difficulty in determining the endogenous loss of P accurately using these procedures and values for total endogenous losses between 8 mg/kg dry matter intake (Akinmusire and Adeola, 2009) and 670 mg/kg dry matter intake (Shen et al., 2002) have been reported..

Total endogenous losses consist of basal endogenous losses and diet specific endogenous losses. The basal endogenous losses are secreted in response to the intake of dry matter and are not related to the diet that is fed. Values for the total endogenous losses of P can be determined by feeding a P-free diet to the animals (Table 1) and collecting feces during a 4 or 5-day period (Petersen and Stein, 2006; Bünzen, 2009). This procedure is relatively simple and much easier and less time consuming than the procedures required for determining total endogenous losses. More importantly, data for basal endogenous losses determined using this procedure are much less variable than values obtained for the total endogenous losses and an average value for basal endogenous losses of approximately 200 mg per kg dry matter intake have been reported. This value is relatively constant among experiments.

CALCULATION OF STANDARDIZED TOTAL TRACT DIGESTIBILITY OF P

By correcting values for the ATTD of P by the basal endogenous losses of P, values for the standardized total tract digestibility (STTD) of P are calculated. It is, therefore, necessary to first calculated the ATTD of P, and then make the correction for the basal endogenous losses. Values for the ATTD of P can be calculated using equation 1 (Almeida and Stein, 2010):

ATTD of P (%) = [(P intake – P output)/P intake] × 100 [1]

Values for STTD of P are calculated by subtracting the basal endogenous losses for P from the output of P before output is subtracted from P intake according to equation 2 (Almeida and Stein, 2010):

STTD of P (%) = [(P intake – (P output - basal endogenous loss))/P intake] × 100 [2]

where P intake, P output, and basal endogenous losses are expressed as gram per day or as gram for the entire collection period.

It follows from the above equations that values for STTD of P can be calculated only if a value for the basal endogenous loss of P is available. As mentioned, this value is determined using a P-free diet, but because the variability among experiments in the determined endogenous loss of P is relatively small, it is not necessary to determine the basal endogenous P in every experiment where the digestibility of P is determined. Thus, it is necessary only to determine the ATTD of P, and by using the average value for basal endogenous losses (200 mg per kg dry matter intake), values for the STTD of P can be calculated.

PRACTICAL DIET FORMULATION

The main disadvantage of using data for ATTD of P is that ATTD values are not always additive in mixed diets because of the influenced of the dietary P level in diets used to determine the ATTD of P.

If a constant value for the basal EPL of pigs is assumed, it is possible to calculate values for STTD of P from experiments that were conducted to determine effects of dietary P on ATTD of P. As an example, in the experiment by Fan et al. (2001), different inclusion rates of soybean meal resulted in diets containing 0.11, 0.21, 0.32, and 0.43% P and the ATTD of P in these diets was 18.8, 37.6, 38.5, and 45.2%, respectively (Table 2). If the ATTD values are corrected for basal endogenous loss of P and if it is assumed that the basal endogenous loss of P is 200 mg/kg dry matter intake, values for the STTD of P can be calculated at 43.4, 48.4, 44.7, and 48.1% for the 4 diets. It is, therefore, apparent that the differences in STTD values among diets are much less than the differences in ATTD values and the effects of the level of dietary P is removed when values for STTD are used. A similar conclusion was reached in a recent experiment (Kim et al., 2010) in which the ATTD and STTD of P in whey powder and 2 sources of whey permeate (Perlac 850 and Variolac 960) were determined. Diets containing whey powder or Perlac 850 contained 0.20% P whereas the diet containing Variolac 960 contained only 0.04% P. The ATTD of P in whey powder and Perlac 850 (84.3 and 86.1%, respectively) were

greater ($P < 0.05$) than in Variolac 960 (55.9%), but for STTD, no differences among the 3 ingredients were calculated (91.2, 93.1, and 91.8%, respectively). Data from both of these experiments, therefore, clearly illustrate that by using values for the STTD of P, effects of dietary P-level are removed. Diets may, therefore, be more accurately formulated if P digestibility values are based on the STTD of P rather than the ATTD of P and values for the STTD of P should be used in practical diet formulation. These principals are equivalent to those previously reported for amino acids, where it was shown that values for standardized ileal digestibility of amino acids are more additive in mixed diets than values for apparent ileal digestibility (Stein et al., 2005). Diets are, therefore, most accurately formulated if values for standardized ileal digestibility of amino acids and values for the standardized total tract digestibility of P are used.

CONCLUSIONS

When practical diets for pigs are formulated, values for the STTD of P in all feed ingredients should be used. These values are calculated by correcting values for the ATTD of P for the basal endogenous loss of P, which average 200 mg per kg dry matter intake. It is, therefore, possible to calculate STTD values for all feed ingredients for which ATTD values exist. By using STTD values in diet formulation, values that are additive in mixed diets are used, which will result in the most accurate prediction of the dietary concentration of digestible P. In addition, the fecal excretion of P can also be calculated, which in turn allows for estimation of P output in the manure of pigs.

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Table 1. Example of P-free diets used to calculate the basal endogenous loss of P

Ingredient, %	Weanling pigs	Growing-finishing pigs
Gelatin	20.00	20.00
Soybean oil	4.00	4.00
Solka floc	4.00	4.00
Ground limestone	0.80	0.80
Sucrose	20.00	20.00
Lactose	20.00	-
Cornstarch	29.22	49.22
Amino acid mixture[1]	0.78	0.78
Sodium chloride	0.40	0.40
Vitamin mineral premix	0.30	0.30
Potassium carbonate	0.40	0.40
Magnesium oxide	0.10	0.10
Total	100.00	100.00

[1]Contain the following AA (%, as-is basis): DL-methionine, 0.27; L-threonine, 0.08; L-tryptophan, 0.14; L-histidine, 0.08; L-isoleucine, 0.16; and L-valine, 0.05.

Table 2. Effect of dietary P concentration on values for apparent (ATTD) and standardized (STTD) total tract digestibility of P [1]

Item	Dietary soybean meal, %			
	13.6	27.3	40.8	54.6
P, g/kg diet DM	1.1	2.1	3.2	4.3
ATTD, %	18.8	37.6	38.5	45.2
STTD[2], %	43.4	48.4	44.7	48.1

[1]Values from Fan et al. (2001). n = 4.

[2]Values for STTD of P were calculated by correcting ATTD values for basal endogenous losses of P. The basal endogenous losses of P were assumed to be 200 mg/kg DMI.

Table 3. Differences in values for apparent total tract digestibility (ATTD) and standardized total tract digestibility (STTD) of P in whey products fed to weanling pigs[1, 2]

	Milk product				
Item	Whey powder	Perlac 850	Variolac 960	SEM	*P*-value
P in diet, %	0.203	0.202	0.040	-	-
ATTD of P	84.3[a]	86.1[a]	55.9[b]	2.08	< 0.001
STTD of P[3]	91.2	93.1	91.8	2.08	0.813

[a,b] Values within a row lacking a common superscript letter are different ($P < 0.05$).

[1]Values from Kim et al. (2010).

[2]Each least squares mean represents 8 observations.

[3]Values for STTD of P were calculated by correcting ATTD values for basal endogenous losses of P. The basal endogenous losses of P were determined at 153 ± 11.2 mg/kg DMI in pigs fed the P-free diet.

Fetal Nutrient Deposition Throughout Gestation

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Summary

With improvements in the genetic potential of sows to produce larger litters of pigs with greater lean growth potential, it is necessary to re-evaluate fetal nutrient deposition in order to provide adequate nutrients to the gestating female to support that fetal development. In the present experiment, crossbred gilts were selected, assigned to dietary treatments, estrus-synchronized, and bred. Gilts were then randomly slaughtered at defined time points throughout gestation (d 0, 43, 58, 73, 91, 101, or 108 of gestation; n = 6 to 12 gilts/time point). Maternal liver, kidney, psoas major muscle sample, uterus, entire placenta, and fetal body and liver were collected for determination of dry matter (DM), N, ether extract (EE), and ash analysis. Trace mineral (Cu, Fe, Mn, Zn, and Se) content of the fetal body and liver and maternal liver were determined by ICP-MS. With regard to stage of gestation, gestation BW gain and fetal crown-rump length increased linearly ($P < 0.01$); weights of uterus and individual fetus increased quadratically ($P < 0.01$) and placenta increased cubically ($P < 0.01$); the maternal liver DM, N, and EE did not change during gestation; fetal DM, N, EE, and ash content increased cubically ($P < 0.01$), with the greatest increase of each component occurring during the last 15 d of development. With regard to trace mineral content, Cu, Fe, Mn, Zn, and Se content in maternal liver did not change during gestation but fetal content increased quadratically ($P < 0.01$), with approximately 50% of total fetal trace mineral content deposited during the last 25 d of gestation. Based on broken-line analysis, the accretion rates of fetal N and trace mineral deposition differed ($P < 0.01$) before and after d 70 of gestation. The results demonstrate the dynamic nutrient deposition that occurs during fetal development in gestation with d 70 of gestation being a critical point when nutrient demand for fetal tissue deposition increases markedly.

Introduction

Great progress has been made in swine production in recent decades. A few producers in some countries have attained production of more than 30 pigs/sow/year (PSY) and it is not uncommon for the top 10% of producers in some countries to be above 27 PSY. While the increase in PSY is positive, there is an average culling rate of 40-50% and a death loss of about 8% annually in modern production systems that are not positive. Mahan and Newton (1995) indicated that body stores of both macro- and microminerals become depleted with advancing parity; and the higher the level of productivity, the greater the degree of depletion. This might indicate greater mineral needs for modern, hyperprolific sows, especially for advanced parities.

Gestation is characterized by a changing nutrient need for the developing fetuses throughout gestation. There is relatively low, almost nonexistent, nutrient need for the developing fetus in early gestation. But, as gestation progresses, nutrient need for tissue deposition in the developing fetuses increases dramatically. The target of feeding gilts or sows during gestation is to obtain optimal fetal growth and proper maternal weight gain. However, current feeding programs for gestating sows are based on a single diet formulated to meet the 'average' nutrient need during gestation, with occasional adjustments made in feeding level not in nutrient concentration

(Trottier and Johnston, 2001). Obviously, it may result in excess nutrients in early gestation and inadequate nutrients in late gestation. In addition, McPherson et al. (2004) indicated that more current fetal weights on d 100 to 114 of gestation were approximately 28 to 30% greater than those reported by Leenhouwers et al. (2002), but up to 50% greater than those reported more than 40 years ago (Ullrey et al., 1965). Any effect of potential mineral inadequacy on sow culling rate or mortality is largely unknown. Mahan (2006) suggest that sows may not meet their biological need for nutrients, particularly the minerals, using nutrient recommendations of the previous decades.

If fetal weight can depict maternal nutrient needs and this deposition is plotted, it follows an obvious exponential curve with increased deposition in the last month before birth and extreme deposition in the week immediately preceding birth. The actual deposition of individual nutrients has not been examined and reported extensively in the refereed literature with the exception of protein and crude fat (McPherson et al., 2004; Ji et al., 2005). With protein, the deposition curve follows that of body weight in general and after about d 69 of gestation there is a great increase in protein deposition, which indicates gilts have about 35% less protein for maternal needs available for maternal growth after d 69 than before. Depending then on the dietary protein supply, either maternal growth or fetal growth may be compromised in late gestation.

There are few published reports of the mineral deposition curve and the determination of whether there is maternal catabolism of body tissue or reductions in maternal tissue content in late gestation to meet the developing fetus need. Mahan et al. (2009) have reported the most complete profile to date of the fetal mineral deposition. Their work used sufficient animals and gestational ages that deposition curves could be developed; further, they noted that about 50% of total fetal/litter mineral was deposited in the last 15 days of gestation. To counter the anticipated greater biological need for minerals by high producing sow lines, most feed industry and university specialists have routinely recommended higher dietary fortification levels of macro- and microminerals in gestation sow diets (Mahan, 2006). Although this practice is perhaps logical and may be what sows need for higher productivities, it is not based on research. And, while this may meet the sow need, unfortunately, it may also result in excess dietary minerals which become a waste management problem.

The purpose of this project was firstly to investigate the nutrient (dry matter, nitrogen, fat, trace minerals) status of gestating swine and developing fetuses at different gestational stages in order to provide a better estimation of the dynamics of nutrient deposition throughout gestation. Secondly, the specific effect of source of Se on tissue mineral content was examined.

Experimental procedures

This experiment utilized a total of 100 crossbred gilts at 6 months of age (183 ± 2.7 days) with an initial body weight (BW) of 137 ± 10 kg. These gilts were examined for structural soundness and general health and were randomly assigned to one of two dietary treatments to receive Se (0.3 mg/kg diet) as Na selenite or organic Se (Sel-Plex®; Alltech Inc., Nicholasville KY) in a common corn-soybean meal diet formulated at or greater than NRC (1998) requirement estimates.

At 8 months of age, the gilts were estrus-synchronized, heat checked, and bred by artificial insemination three times during an estrous cycle. Bred animals continued on their diet and were slaughtered at defined time points throughout gestation. Gilts were fed a single meal of 2.73 kg/d (as-fed basis) during gestation that provided 14.5 and 329.2 g/d of true ileal-digestible lysine and protein, respectively.

Slaughter time points: A total of 8 gilts were slaughtered at 6 months age, immediately prior to diet assignment to provide the initial nutrient content of selected tissues. The remaining 92 gilts continued on this experiment. Six gilts were slaughtered again at mating (about 2 months later) to provide pre-breeding baseline nutrient values. Bred females that conceived were assigned randomly to be slaughtered at d 43, 58, 73, 91, 101, or 108 of gestation. Females that were bred but did not conceive (open gilts) continued on gestation diet and were assigned to a final slaughter date (d 120) to provide data of the difference in maternal tissue nutrient content simply due to pregnancy when compared to gilts slaughtered at d 101 and 108.

Slaughter and sample collection: Upon reaching their designated harvest date (± 1 d), gilts were transported to the University of Kentucky Meat Laboratory and then slaughtered in compliance with

standard UK Meats Laboratory procedures. Gilts were weighed, electrically stunned, and killed by exsanguination. Maternal tissues and reproductive tracts were then collected. Placental units were separated from the uterine horn and then fetuses were removed from the placental units. Fetal numbers, position, and gender were recorded with each fetus weighed. The liver and the gastrointestinal tract (GIT) from the fetal bodies were collected. The weights of fetal tissues were recorded and fetuses from each litter were stored collectively. All collected samples were placed on ice, and frozen (-20°C) until they were later processed.

Sample analysis: All the collected samples and the whole fetal body were ground and thoroughly mixed. Subsamples were taken and lyophilized. Dry matter (DM) content, nitrogen and ether extract were determined for all samples. Fetal body, fetal liver, and sow liver samples were subsequently analyzed for Se, Cu, Fe, Mn, and Zn by inductively coupled plasma (ICP) mass spectrometry (MS) with National Institute of Standards and Technology (NIST) standards used for quality control. Prior to ICP-MS analysis, samples were digested with nitric acid in a pressurized microwave (MDS-2000, CEM Corporation, Matthews, NC) and appropriately diluted.

Statistical analysis: The data were analyzed as a completely randomized design. Analyses were performed using the GLM procedure of SAS® (SAS Inst., Inc., Cary, NC). Gilt and associated litter was the experimental unit. The statistical model included day of gestation and source of Se as main effects. Data were also analyzed using PROC REG of SAS® with the forward option to describe the quantitative (linear, quadratic, or cubic) changes of each tissue as day of gestation progressed. Responses that could be explained by quadratic or cubic regressions were further analyzed to find the breakpoint (day of gestation) where the rate of accretion changed at $\alpha = 0.05$. The SAS® NLIN two-slope, straight broken-line procedure was used to obtain those breakpoints (Robbins et al., 2006).

Results

Reproductive characteristics: Table 1 summarizes the reproductive characteristics during gestation. From d 43 to 108 of gestation, slaughter BW of gilts increased linearly ($P < 0.01$) as did gestation BW gain ($P < 0.01$). The weight of maternal liver remained constant during this period of time as did the weight of kidney. The weight of ovaries changed in a cubic fashion ($P < 0.01$). As gestation progressed, the weight of uterus increased quadratically ($P < 0.01$). The weights of individual placenta and entire placenta increased cubically ($P < 0.01$).

The weights of individual fetus and whole litter increased quadratically ($P < 0.01$; Table 1 and Figure 1) and crown-rump length increased linearly ($P < 0.01$) with advancing gestation. The weight of fetal liver increased linearly ($P < 0.01$) and the weight of the GIT increased quadratically ($P < 0.01$) from 58 to 108 days of gestation. The breakpoint of total uterus weight occurred at d 98.6, suggesting that uterus deposition rate increased dramatically during last two weeks of gestation. The breakpoint of total placental weight occurred at d 69, demonstrating decreased placenta deposition rate during the second half of gestation. The breakpoint of the weights of individual fetus and whole litter occurred at d 67.8 and 69.1, respectively, showing that fetal growth mainly occurred after d 70 of gestation (Figure 1).

Weights of nutrient components in various tissues of gilts and fetuses: Table 2 provides the weight of nutrient components in various tissues of gilts and fetuses. From d 43 to 108 of gestation, the contents of DM, N, and EE in maternal liver remained constant ($P > 0.17$). In uterus, DM and N content increased quadratically ($P < 0.01$) and EE increased cubically ($P < 0.01$) during this period. For the entire placenta during d 43 to 108 of gestation, DM, N, and EE increased linearly ($P < 0.01$).

The DM, N, EE, and ash content of the individual fetuses and the total litter increased cubically ($P < 0.01$) as gestation progressed (see Figure 2 for nitrogen accretion in fetus) with the greatest increase of each component occurring during the last 15 d of development.

The breakpoint of nitrogen retention in uterus, individual fetus, and whole litter occurred at d 97.2, 85.8, and 88.6, respectively, showing that nitrogen accretion mainly occurred after d 90 of gestation (see Figure 2 for nitrogen accretion breakpoint in fetus). In other words, tremendous protein requirement in sows is occurring after d 90 of gestation.

Trace mineral contents in maternal and fetal livers: Table 3 provides trace mineral content in maternal and fetal livers at different days of gestation. Generally speaking, in maternal liver, there

was no trend for trace mineral deposition during d 43 to 108 of gestation with an exception of quadratic pattern in Cu ($P < 0.05$). In fetal liver, total Cu increased quadratically ($P < 0.01$); total Fe increased cubically ($P < 0.01$) with the greatest deposition occurring at d 91 of gestation; total Mn and Zn increased linearly ($P < 0.01$); and total Se content in pooled data showed a quadratic increase ($P < 0.01$) during gestation.

Trace mineral content in individual fetus and whole litter: Table 4 shows trace element contents in individual fetus and whole litter at different days of gestation. Generally, trace mineral depositions in fetus increased cubically for Cu ($P < 0.01$) and quadratically ($P < 0.01$) for Fe, Mn, Zn, and Se, with approximately 50% of total mineral content deposited during d 91 to 108 of gestation. In the whole litter, deposition of those trace minerals showed a similar trend as in the individual fetus ($P < 0.01$). In addition, Fe content in individual fetus was over two-fold of the total content of other trace minerals after day 73 of gestation, which may indicate the great demand for iron during late gestation.

The breakpoint of trace mineral deposition in individual fetus occurred at d 91.0 for Cu ($P < 0.01$; Figure 3), at d 70.1 for Fe ($P < 0.01$; Figure 4), at d 67.0 for Mn ($P < 0.01$; Figure 5), and at d 84.0 for Zn ($P < 0.01$; Figure 6), showing that trace mineral deposition in the fetus mainly occurred after d 70 of gestation. In other words, tremendous trace mineral requirement is occurring after d 70 of gestation and, in particular, during d 90 to 108 of gestation. With regard to the Se treatment, it is interesting to see slightly different fetal Se deposition between organic Se and inorganic Se with more Se deposition in late gestation from organic Se compared to the selenite form (Figures 7 and 8). The breakpoint of deposition occurred at d 86.8 and d 69.6 for the organic and inorganic forms, respectively; during the initial phase and during the acceleration phase, the deposition rate for the organic form was about double that of the inorganic.

Summary

Weight and composition changes in maternal tissues and the conceptus occurred at various rates during gestation, implying that maternal nutrient needs for supporting these dynamic changes vary during gestation (see Table 5 for summary).

During gestation, dynamic nutrient change occurs in fetal and maternal tissues. For the fetus, the fetal DM, N, EE, ash, and trace mineral accretion rates in individual fetus increased tremendously during late gestation, indicating a great nutritional demand for all major nutrient components during this particular period. Based on SAS® NLN broken-line analysis, fetal weight and nutrient component differs before and after d 70 of gestation, with the greatest deposition occurring at last 25 day of gestation. Therefore, the conventional feed strategy has been challenged and nutrients supplied in the sow diet during late gestation may need to be reevaluated.

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Table 1. Weights or characteristics of maternal and fetal tissues at different days of gestation

	Day of gestation[1]						
	43	58	73	91	101	108	rMSE[2]
No. of Gilts	8	12	11	12	11	11	
Breeding age, d	259.8	262.8	266.7	261.6	264.6	274.6	6.63
Breeding BW, kg	177.5	167.8	171.7	169.8	166.5	175.8	10.93
Slaughter BW, kg[5]	202.9	200.2	215.0	222.9	219.8	241.3	11.22
Gestation gain, kg[5]	25.52	32.39	43.36	53.11	53.29	65.65	6.02
Liver, kg	1.75	1.73	1.66	1.64	1.66	1.76	0.17
Kidney, g[3]	190.7	189.9	191.1	185.5	179.1	195.2	30.5
Ovaries, g[7]	18.40	20.90	20.47	19.00	20.88	23.68	5.68
Empty uterus, kg[6]	2.44	2.90	3.51	3.99	4.74	5.93	0.68
Total placenta, kg[7]	0.98	2.14	3.49	3.48	3.32	4.25	0.75
Corpora lutea, n	15.38	13.92	16.52	15.67	16.30	17.60	2.44
Total fetuses, n	12.50	11.42	12.98	12.25	13.07	13.07	2.39
Live fetuses, n	12.50	11.33	11.88	12.00	12.62	12.87	2.32
Fetus, g[6]	16.1	104.9	343.8	752.9	979.5	1360.4	116.5
Whole litter, kg[6]	0.22	1.24	4.15	8.82	12.32	17.46	1.73
Fetal length, cm[5]	6.08	12.38	18.71	24.01	27.14	30.84	1.29
Fetal liver, g[5]	-	7.29	17.61	31.31	33.45	45.32	4.33
Fetal GIT, g[6]	-	2.89	14.79	42.02	60.10	84.11	7.97
Fetal placenta, g[4,7]	78.2	186.4	271.6	288.4	256.5	340.3	54.7

[1] Days of gestation indicated above were the average of defined slaughter period, individual gestation day of gilt = average ± 1day and regression analysis limited 43 to 108 days of gestation.

[2] rMSE - Root mean square error; when divided by the square root of the number of observations provides the standard error associated with each mean.

[3] Kidney was collected only from the left side of the gilts.

[4] Fetal placenta weights were the total weight of placenta divided by the total number of fetuses.

[5] Linear response, $P < 0.01$.

[6] Quadratic response, $P < 0.01$.

[7] Cubic response, $P < 0.01$.

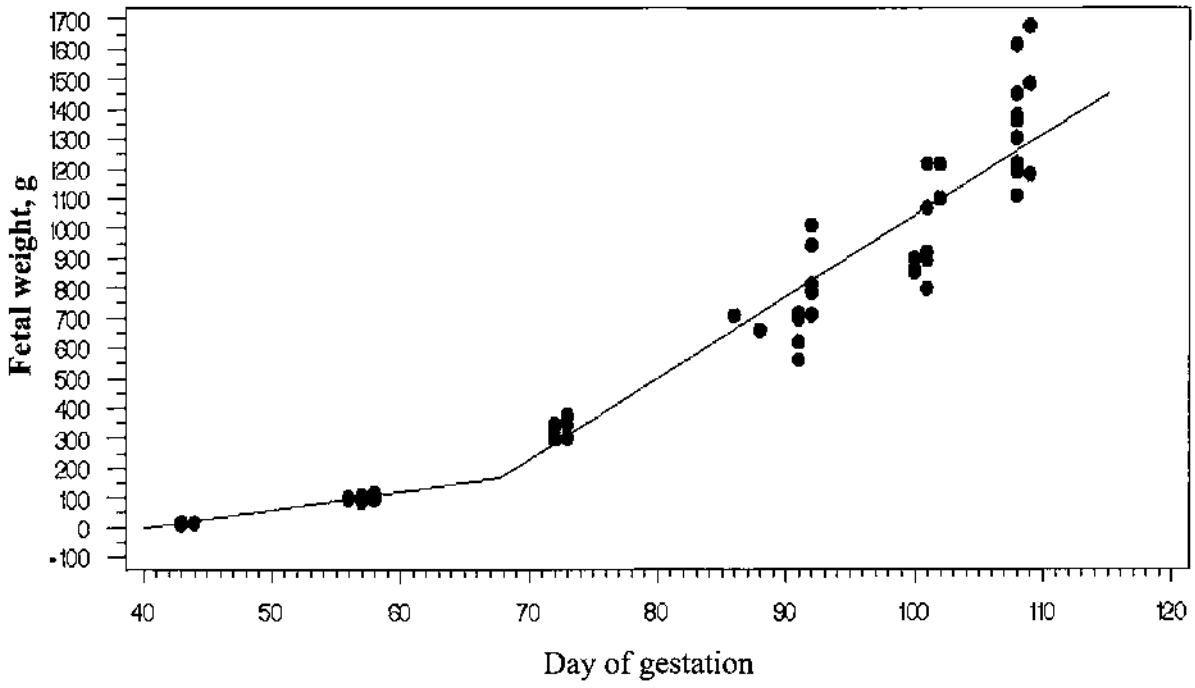

Figure 1. Fetal weight broken-line analysis from d 43 to 108 of gestation (n = 65 litters). Breakpoint of the fetal weight (g) occurred at d 67.8 of gestation ($R^2 = 0.94$, $P < 0.01$), showing that fetal growth mainly occurred after d 67.8 of gestation; the regression equation before d 67.8 was: 6.2097 × (d - 67.8) + 168.70. After d 67.8 the equation was: 27.2219 × (d - 67.8) + 168.70, where d is day of gestation.

Table 2. Weight (grams) of nutrient components in various maternal and fetal tissues at different days of gestation

	Day of gestation[1]						
	43	58	73	91	101	108	rMSE[2]
Gilts, n =	8	12	11	12	11	11	
Maternal liver							
DM	528.3	522.3	507.4	507.2	507.6	526.7	55.72
N	58.34	57.17	54.95	56.87	58.94	57.35	6.32
EE	29.30	25.01	26.26	32.41	27.70	34.60	7.93
Uterus							
DM[4]	297.7	343.0	429.7	520.5	653.4	827.0	87.5
N[4]	38.30	46.71	55.80	67.71	84.54	105.38	11.86
EE[5]	5.52	7.39	10.85	12.39	15.24	22.00	3.11
Total placenta							
DM[3]	65.4	122.2	236.4	296.8	309.0	412.5	67.0
N[3]	6.49	12.27	25.67	32.30	33.90	45.35	7.98
EE[3]	2.20	4.10	8.91	13.42	12.37	15.03	2.65
Whole litter							
DM[5]	21.7	138.4	475.7	1173.7	1930.7	3065.6	304.8
N[5]	2.24	13.58	45.32	108.75	177.69	281.40	29.61
EE[5]	0.92	8.01	27.22	73.30	114.27	185.60	23.38
Ash[5]	2.93	25.30	98.11	217.73	363.79	549.75	14.88
Fetus							
DM[5]	1.61	11.70	39.40	100.61	153.39	238.49	19.27
N[5]	0.17	1.15	3.76	9.34	14.12	21.85	1.83
EE[5]	0.07	0.68	2.26	6.27	9.08	14.40	1.52
Ash[5]	0.22	2.14	8.13	18.65	28.88	43.02	1.18

[1] Days of gestation indicated above were the average of defined slaughter period, individual gestation day of gilt = mean ± 1day and regression analysis limited 43 to 108 days of gestation.

[2] rMSE - Root mean square error; when divided by the square root of the number of observations provides the standard error associated with each mean.

[3] Linear response, $P < 0.01$.

[4] Quadratic response, $P < 0.01$.

[5] Cubic response, $P < 0.01$.

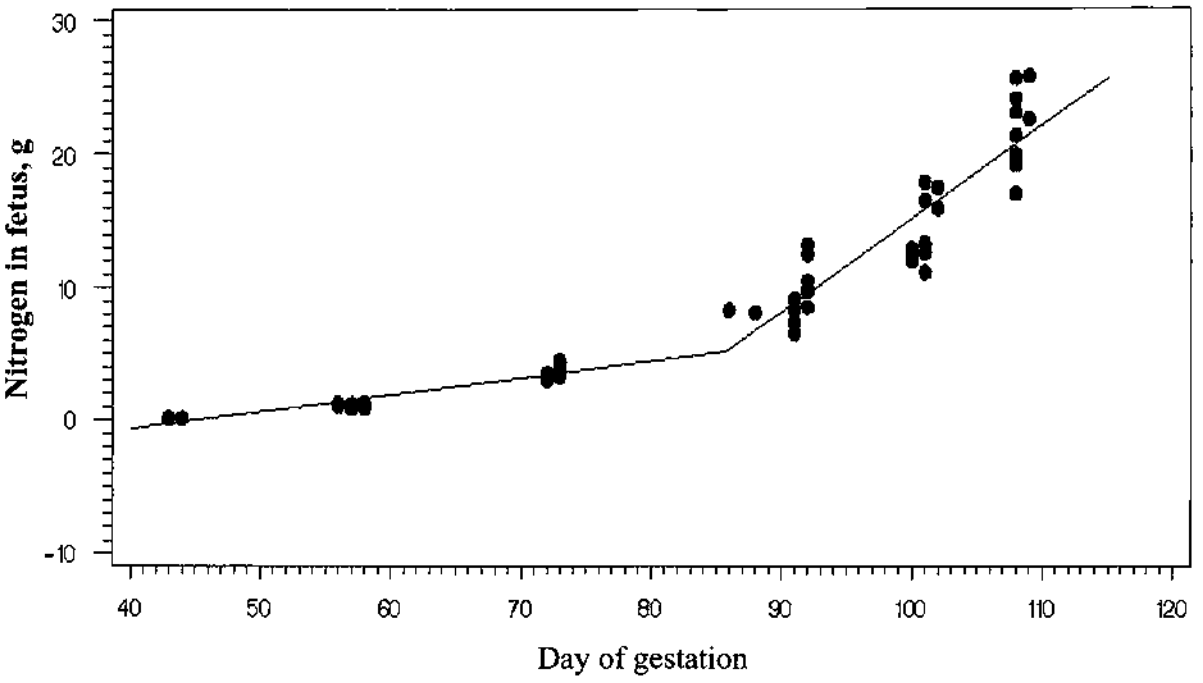

Figure 2. Fetal nitrogen broken-line analysis from d 43 to 108 of gestation (n = 65 litters). Breakpoint of the nitrogen in fetus (g) occurred at d 85.8 of gestation ($R^2 = 0.95$, $P < 0.01$), showing that fetal nitrogen accretion mainly occurred after d 85.8 of gestation; the regression equation before d 85.8 was: 0.1263 × (d - 85.8) + 5.1865. After d 85.8 the equation was: 0.7007 × (d - 85.8) + 5.1865, where d is day of gestation.

Table 3. Trace mineral content (mg) in maternal and fetal liver at different days of gestation

	Day of gestation[1]						
Variable	43	58	73	91	101	108	SEM
Gilts	8	8	8	8	8	8	
Maternal liver							
Cu[4]	72.62	114.28	90.73	60.37	61.94	88.43	14.47
Fe	333.3	325.5	320.6	305.0	339.2	313.0	28.46
Mn	3.03	3.08	3.21	2.91	3.10	2.91	0.13
Zn	133.9	114.2	143.1	100.3	134.9	137.8	10.39
Se	1.29	1.24	1.25	1.26	1.35	1.30	0.08
Fetal liver[2]							
Cu[5]	-	0.77	1.06	1.31	1.99	2.11	0.12
Fe[6]	-	1.14	3.32	8.62	8.05	8.18	0.47
Mn[3,7]	-	9.98	21.01	33.33	35.99	43.58	3.08
Zn[7]	-	1.18	1.83	3.73	4.61	4.12	0.46
Se[3, 5]	-	3.68	5.54	8.10	11.12	15.71	0.69

[1] Days of gestation indicated above were the average of defined slaughter period, individual gestation day of gilt = mean ± 1day and regression analysis limited to d 43 to 108 of gestation in maternal liver and d 58 to 108 of gestation in fetal liver.

[2] Each value of fetal liver was pooled from three fetal livers in one litter and data were from d 58 to 108.

[3] Unit as microgram (μg).

[4] Cubic response, $P = 0.03$.

[5] Quadratic response, $P < 0.01$.

[6] Cubic response, $P < 0.01$.

[7] Linear response, $P < 0.01$.

Table 4. Trace element content (mg) in individual fetus and whole litter at different days of gestation[1]

Variable	Day of gestation						SEM[2]
	43	58	73	91	101	108	
Litters	8	8	8	8	8	8	
Fetus[3]							
Cu[6]	0.24	0.89	1.20	1.67	2.56	3.11	0.12
Fe[5]	0.49	2.97	9.58	24.22	30.48	46.59	1.56
Mn[5]	0.004	0.049	0.133	0.331	0.362	0.492	0.024
Zn[5]	0.27	2.03	4.50	9.89	13.88	18.08	0.61
Se[5]	0.002	0.012	0.033	0.077	0.111	0.162	0.006
Whole litter[4]							
Cu[6]	3.03	10.17	15.24	19.45	33.14	41.07	1.56
Fe[5]	6.12	33.89	121.57	285.07	394.85	609.37	14.06
Mn[5]	0.051	0.562	1.684	3.861	4.685	6.449	0.245
Zn[5]	3.44	22.98	57.80	117.59	178.43	241.33	9.77
Se[5]	0.024	0.138	0.424	0.899	1.443	2.127	0.062

[1] Days of gestation indicated above were the average of defined slaughter period, individual gestation day of gilt = mean ± 1day and regression analysis limited to d 43 to 108 of gestation.
[2] Standard error of mean.
[3] Each litter fetal value represents a value from three pooled fetuses.
[4] Trace element content in litter = the average of element content in fetus × litter size of gilts.
[5] Quadratic response, $P < 0.01$.
[6] Cubic response, $P < 0.01$.

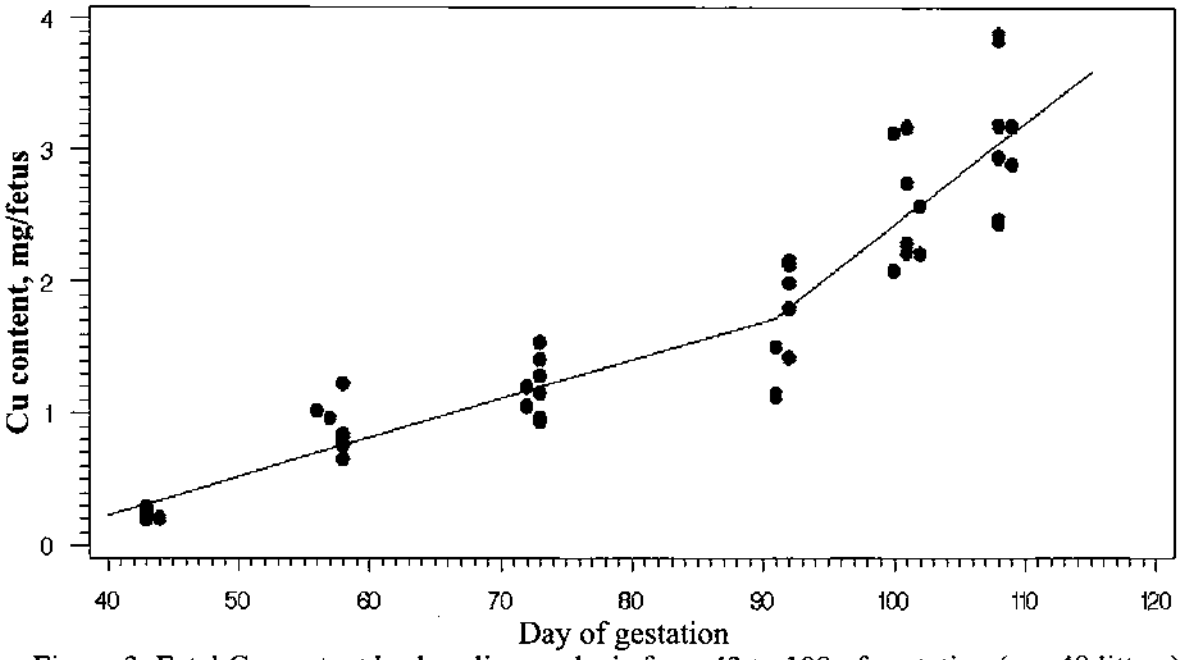

Figure 3. Fetal Cu content broken-line analysis from 43 to 108 of gestation (n = 48 litters) Breakpoint of Cu content in fetus (mg) occurred at d 91.0 of gestation ($R^2 = 0.89$, $P < 0.01$), showing that fetal Cu deposition accretion mainly occurred after d 91.0 of gestation; the regression equation before d 91.0 was: 0.0296 × (d - 91.0) + 1.7389. After d 91.0 the equation was: 0.0773 × (d - 91.0) + 1.7389, where d is day of gestation.

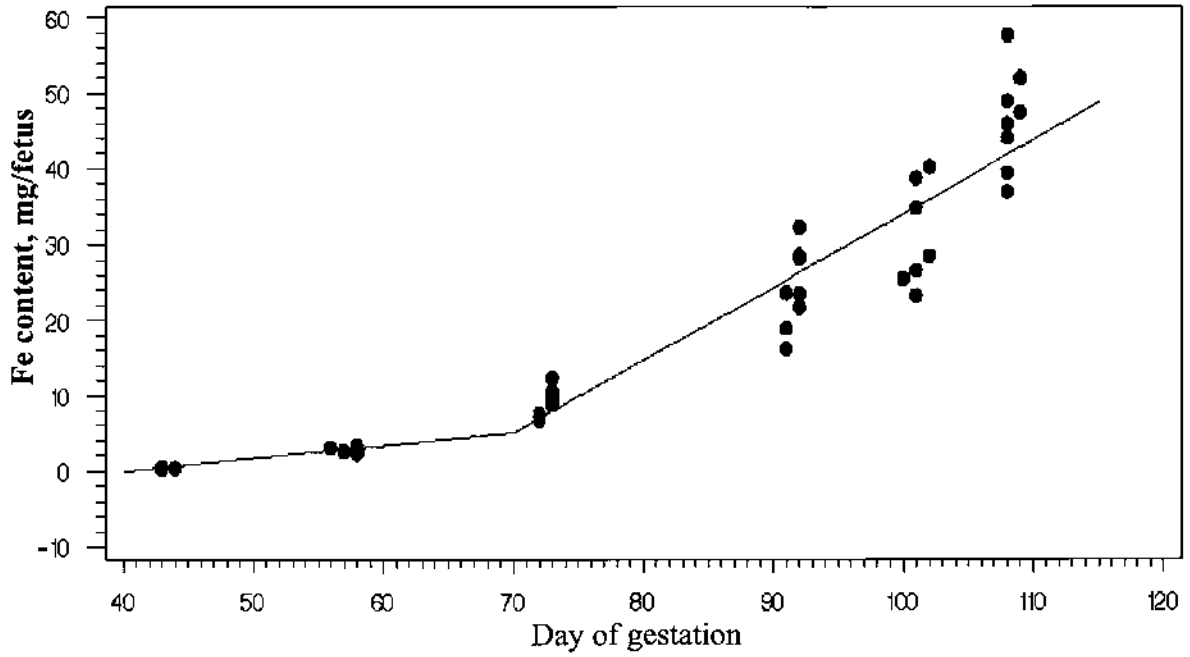

Figure 4. Fetal Fe content broken-line analysis from 43 to 108 of gestation (n = 48 litters) Breakpoint of the Fe content in fetus (mg) occurred at d 70.1 of gestation ($R^2 = 0.92$, $P < 0.01$), showing that fetal Fe deposition accretion mainly occurred after d 70.1 of gestation; the regression equation before d 70.1 was: 0.1715 × (d - 70.1) + 5.0995. After d 70.1 the equation was: 0.9695 × (d - 70.1) + 5.0995, where d is day of gestation.

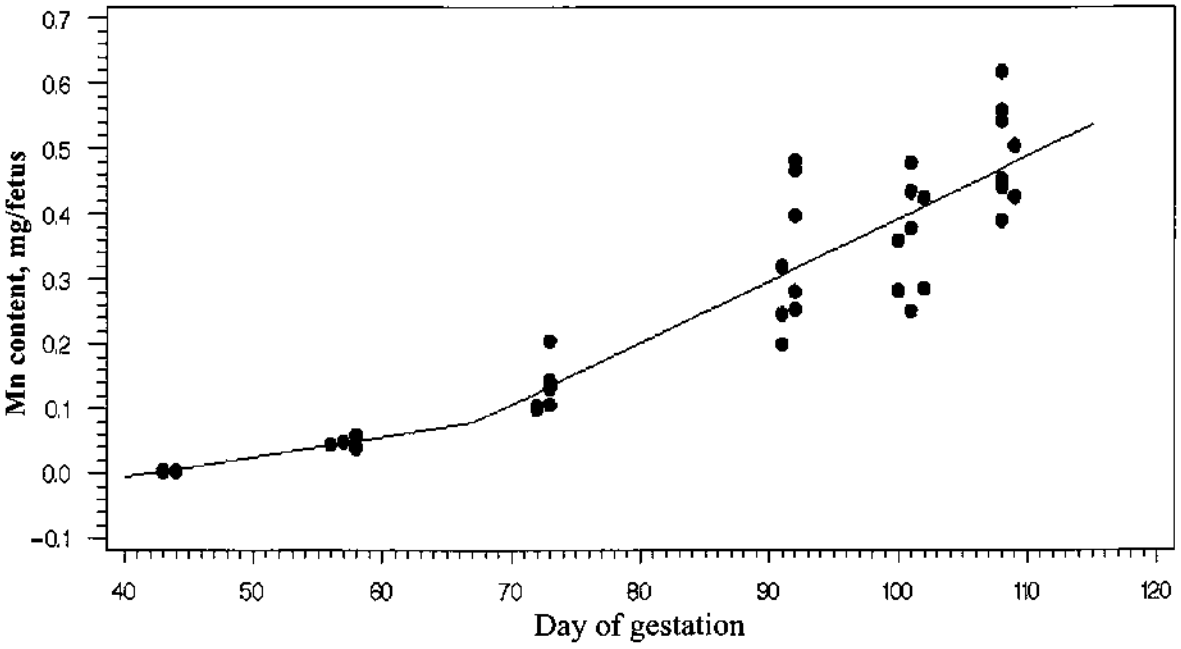

Figure 5. Fetal Mn content broken-line analysis from 43 to 108 of gestation (n = 48 litters) Breakpoint of Mn content in fetus (mg) occurred at d 67.0 of gestation ($R^2 = 0.89$, $P < 0.01$), showing that fetal Mn deposition accretion mainly occurred after d 67.0 of gestation; the regression equation before d 67.0 was: 0.00315 × (d - 67.0) + 0.0786. After d 67.0 the equation was: 0.00951 × (d - 67.0) + 0.0786, where d is day of gestation.

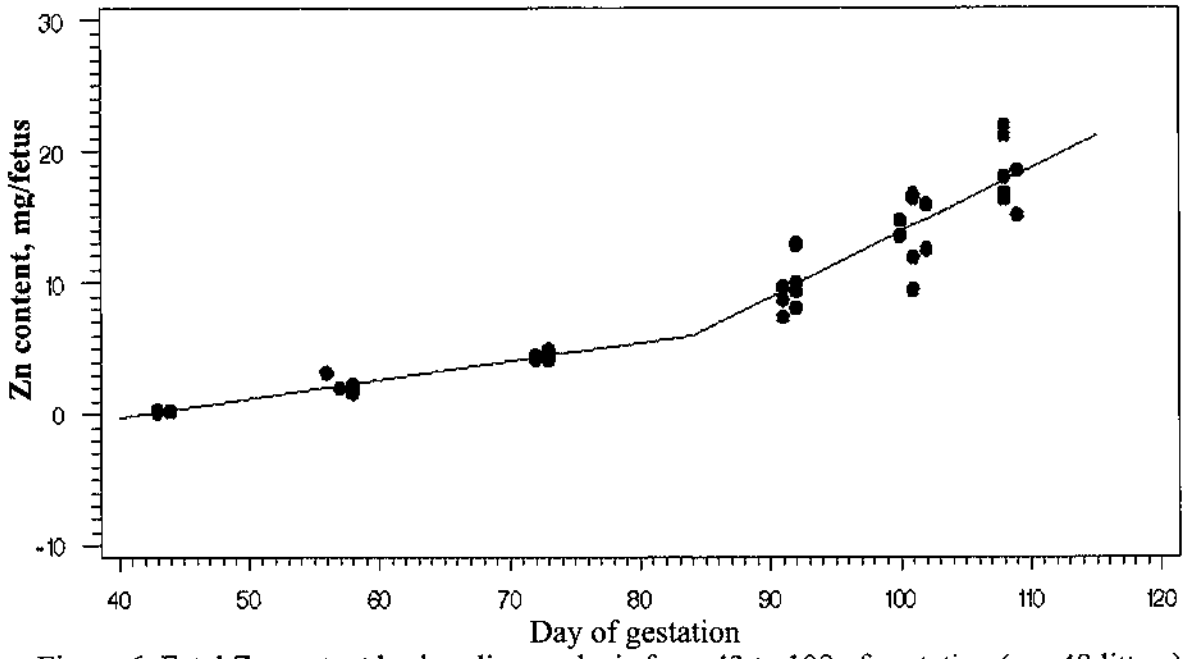

Figure 6. Fetal Zn content broken-line analysis from 43 to 108 of gestation (n = 48 litters) Breakpoint of Zn content in fetus (mg) occurred at d 84.0 of gestation ($R^2 = 0.94$, $P < 0.01$), showing that fetal Zn deposition accretion mainly occurred after d 84.0 of gestation; the regression equation before d 84.0 was: 0.1428 × (d - 84.0) + 5.9970. After d 84.0 the equation was: 0.4876 × (d - 84.0) + 5.9970, where d is day of gestation.

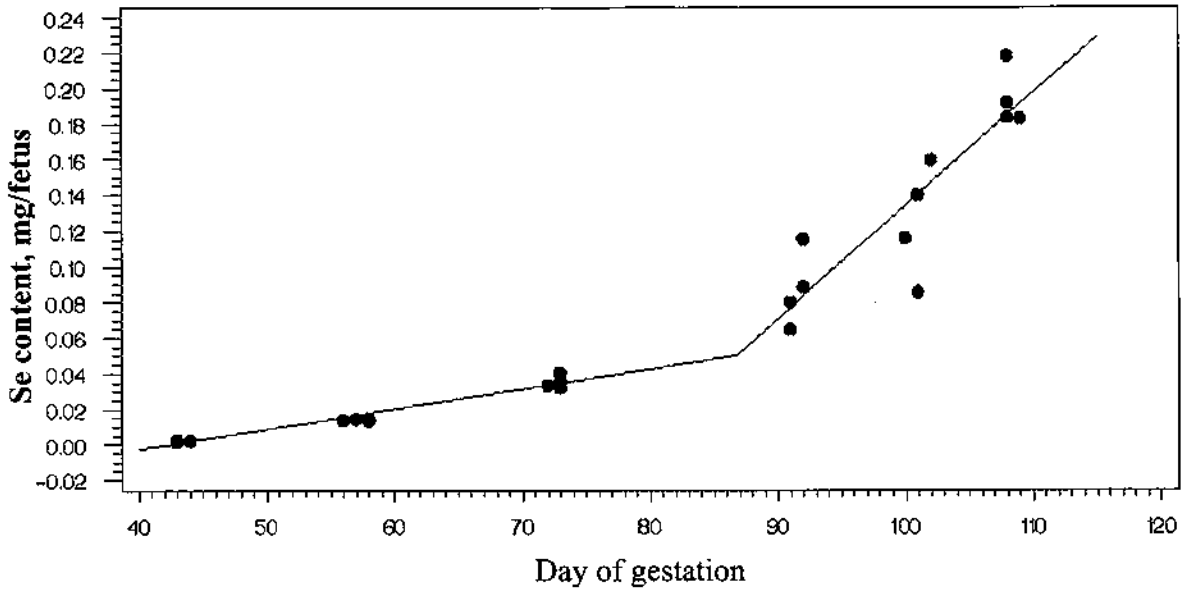

Figure 7. Fetal Se content broken-line analysis from d 43 to 108 of gestation (n = 24 litters; Sel-Plex® treatment).Breakpoint of Se content in fetus (mg) from Sel-Plex® treatment occurred at d 86.8 of gestation ($R^2 = 0.95$, $P < 0.01$), showing that fetal Se deposition accretion mainly occurred after d 86.8 of gestation; the regression equation before d 86.8 was: 0.00113 × (d - 86.8) + 0.0502. After d 86.8 the equation was: 0.00633 × (d - 86.8) + 0.0502, where d is day of gestation.

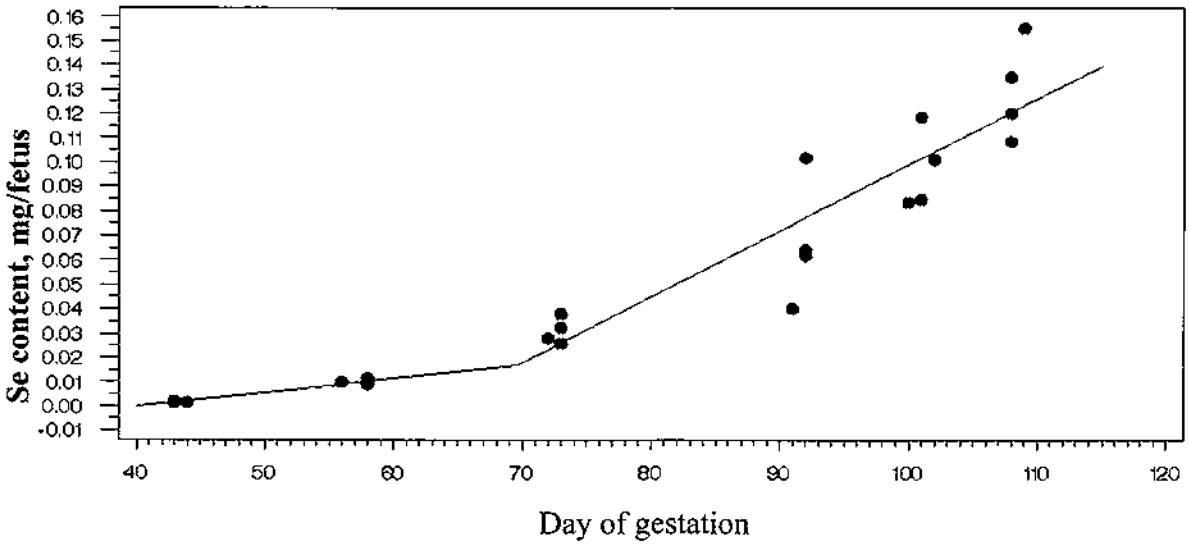

Figure 8. Fetal Se content broken-line analysis from d 43 to 108 of gestation (n = 24 litters; Selenite treatment).Breakpoint of Se content in fetus (mg) from selenite treatment occurred at d 69.6 of gestation ($R^2 = 0.92$, $P < 0.01$), showing that fetal Se deposition accretion mainly occurred after d 69.6 of gestation; the regression equation before d 69.6 was: 0.00058 × (d – 69.6) + 0.0169. After d 69.6 the equation was: 0.00270 × (d – 69.6) + 0.0169, where d is day of gestation.

Table 5. Composition change in maternal tissue and fetus during gestation[1]

	Day of gestation							Break
Variable	43	58	73	91	101	108	**115**	point
Gestation gain, kg	25.5	32.4	43.4	53.1	53.3	62.7	**66.3**	-
Uterus								
Weight, kg	2.44	2.90	3.51	3.99	4.74	5.93	**6.32**	98.6
DM, g	297.7	343.0	429.7	520.5	653.4	827.0	**904.5**	90.2
N, g	38.3	46.7	55.8	67.7	84.5	105.4	**114.8**	97.2
EE, g	5.52	7.39	10.85	12.39	15.24	22.00	**27.69**	99.2
Total placenta								
Weight, kg	0.98	2.14	3.49	3.48	3.32	4.25	**4.53**	69.5
DM, g	65.4	122.2	236.4	296.8	309.0	412.5	**415.9**	-
N, g	6.49	12.27	25.67	32.30	33.90	45.35	**45.83**	-
EE, g	2.20	4.10	8.91	13.42	12.37	15.03	**16.21**	-
Fetus								
Length, cm	6.08	12.38	18.71	24.01	27.14	30.84	**33.00**	-
Weight, g	16.1	104.9	343.8	752.9	979.5	1360.4	**1587.7**	67.8
DM, %	10.00	11.14	11.46	13.30	15.62	17.56	**20.31**	88.2
DM, g	1.61	11.70	39.40	100.61	153.39	238.49	**324.29**	85.7
N, g	0.17	1.15	3.76	9.34	14.12	21.85	**29.06**	85.8
EE, g	0.07	0.68	2.26	6.27	9.08	14.40	**19.06**	84.8
Ash, g	0.22	2.14	8.13	18.65	28.88	43.05	**50.71**	71.0
Cu, mg	0.24	0.89	1.20	1.67	2.56	3.11	**4.07**	91.0
Fe, mg	0.49	2.97	9.58	24.22	30.48	46.59	**53.99**	70.1
Mn, mg	0.00	0.05	0.13	0.33	0.36	0.49	**0.57**	67.0
Zn, mg	0.27	2.03	1.50	9.89	13.88	18.08	**21.26**	84.0
Se, mg	0.00	0.01	0.03	0.08	0.11	0.16	**0.19**	71.9
Whole litter								
Weight, kg	0.22	1.24	4.15	8.82	12.32	17.46	**20.31**	69.1
DM, g	21.7	138.4	475.7	1173.7	1930.7	3065.6	**4178.56**	91.5
N, g	2.24	13.58	45.32	108.75	177.69	281.40	**385.57**	88.6
EE, g	0.92	8.01	27.22	73.30	114.27	185.60	**247.95**	87.4
Ash, g	2.93	25.30	98.11	217.73	363.79	549.75	**739.88**	71.8
Cu, mg	3.03	10.17	15.24	19.45	33.14	41.07	**55.35**	92.0
Fe, mg	6.12	33.89	121.57	285.07	394.85	609.37	**705.87**	70.4
Mn, mg	0.05	0.56	1.68	3.86	4.69	6.45	**7.48**	67.8
Zn, mg	3.44	22.98	57.80	117.59	178.43	241.33	**281.65**	72.0
Se, mg	0.02	0.14	0.42	0.90	1.44	2.13	**2.49**	88.2

[1] Days of gestation indicated above were the average of defined slaughter period, individual gestation day of gilt = mean ± 1day and regression analysis limited 43 to 108 days of gestation and the values of d 115 were predicted values based on the regression equation.

Feeding the World

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Summary

The grand challenge of feeding the world during coming decades has two components, food sufficiency (producing enough food) and food security (ensuring that everyone has access to enough). We have been remarkably successful in food sufficiency, but we have failed miserably in food security. We must continue to increase food production in the face of significant constraints. Our success in improving food security will depend on success in reducing poverty. Food aid is not the solution to the challenge, but a few components of the solution are proposed.

Introduction

Providing enough food for the people of the world will arguably be one of the grand challenges of humanity during the coming decades. Our recent history on this challenge is one of remarkable success alongside disappointing failure.

The challenge of feeding the world can be easily disaggregated into its two components:

1. Food sufficiency: Producing enough food
2. Food security: Ensuring that all people have access to enough food every day

We have been very successful in our efforts to increase total food production, but we have failed to ensure food security. These two components are distinct, but they are closely related. We certainly cannot have food security without food sufficiency, and our experiences with global food prices since 2007 confirm their relationship.

Food Sufficiency

The human population of the world has increased dramatically during recent decades, and that has strained many of the world's systems, including the food production system. The good news is that we have increased food production even more. In fact, during the latter part of the 20th century we doubled global food production in the astonishingly short time of 3 decades. In my view, this is one of the most impressive accomplishments in the history of mankind!

But there are two important points to be made about that remarkable success. First, it didn't just happen. It happened because we made it happen. We made the necessary investments in research, in extension and in education. We created the market-based systems that provided proper incentives and rewards for risk-taking, creativity and hard work. And we made it happen.

Second, in spite of this remarkable success, we are still not producing enough food. The high and volatile food prices the world has seen since 2007 suggest a precarious supply relative to demand that is easily thrown into imbalance by perturbations such as regional droughts. Closer to home, the U.S. corn carryout (the amount of old-crop corn remaining when harvest of the new crop begins) is projected this year to be only about 2-3 weeks' supply, down from about 6-8 weeks' supply during recent years. The soybean carryout has been about 2-3 weeks' supply for the last few years. It's not clear to me how much carryout is optimal, but two weeks scares me.

But what does the future hold? The United Nations (UN) projects that the world must double crop production again (or increase it by 70%, depending on which UN document you read) by 2050. About half of the projected increase in need is attributable to the expected increase in the number

of people to be fed. The rate of population increase on a percentage basis will be smaller than in the recent past, but on an absolute basis we will continue to add about as many people per decade as during recent decades. So the challenge continues. The rest of the projected increase in needs comes from a truly wonderful development – the growing purchasing power of many poor people around the world. This increased purchasing power leads to improved diets that include more animal products, and the inevitable inefficiency of producing animals increases the challenge of producing enough food.

Unfortunately, we will have important constraints on our ability to produce enough food within the constraints of the earth's resources. For example:

- There is not much new land to be brought into production. In fact, we will actually lose land from food production in the developed world. Fortunately, there is land in the world that can be used much more productively than it is now.
- Water supplies for irrigation are dwindling in some areas, so we will probably irrigate less land in the future than we do now.
- Increasingly tight supplies of fossil fuels will impact agriculture in several ways, notably in the energy-intensive production of nitrogenous fertilizers.
- The diversion of large amounts of material from the food chain to fuel production increases the challenge markedly.
- Global climate change will have impacts that are difficult to project quantitatively. It is likely that production of specific crops will shift geographically; that within an area there will be shifts from one set of crop to another. There are legitimate disagreements about the magnitude of the impact of climate change, but it seems clear that it will be at least disruptive to our attempts to again double food production.

This is not to suggest that we cannot meet the target of doubling food production again in the next 40 years. Personally, I am not pessimistic. I do recognize that we must approach the challenge with all of the investment, energy and creativity we can muster if we are to succeed.

Food Security

Our record on food security has been dismal. There are now more than a billion food-insecure people in the world.

During the quarter-century beginning in 1970 we gradually reduced the number of food-insecure people in the world, but only down to about 800 million. Then during the next decade the number increased but the percentage of the world's people who were food-insecure decreased. Unfortunately, during the last 5 years or so both the number and the percentage of people who are food-insecure have increased sharply.

Note that this discussion has been only about the number of people who do not have reliable access to enough food energy and protein. A much larger number suffer from inadequate intake of micronutrients such as iron, iodine, zinc, vitamin A and folic acid. That is an important discussion in itself, but is outside the bounds of this paper.

It is useful to consider the geography of food insecurity. More than half of the food-insecure people live in Asia, with India having the most, followed by China. Sub-Saharan Africa has the highest percentage of food-insecure people, so much attention is focused there. In another dimension food insecurity is disproportionately rural, which many people find counter-intuitive.

Wars, local droughts, inept and corrupt governments all contribute to food insecurity. However, the dominant reason for food insecurity is poverty. We will solve the food-insecurity problem to the extent we solve the poverty problem.

What's the Answer?

How do we meet the challenge of feeding the world, addressing both of the twin challenges of food sufficiency and food security? A full answer is far beyond the bounds of both this paper and my capacity, but I offer below a few suggested components of the answer.

But first, it is necessary to indicate that food aid is not the answer, for two reasons. First, it doesn't produce anything so it does not contribute to food sufficiency. Second, unless used very carefully food aid can impair or even destroy local agriculture in the recipient country.

I suggest the following 4 items should be components of the answer to feeding the world:

1. *Recognize and acknowledge the problem.* This may be the most difficult. Until we as a society acknowledge that feeding the world will be an important challenge, we will not make the investments and do the things necessary to be successful.
2. *Innovate.* Meeting the challenge of feeding the world is not beyond our capacity, but it will require creativity. We must ensure the widespread adoption of market-based systems that will encourage and reward risk-taking, innovation and hard work.
3. *Invest.* As in the past, we must make both public and private investments in research, education, extension, and agricultural development programs.
4. *In developing countries, start with what is there.* Encourage existing commercial farmers and associated companies in order to maximize the probability of lasting benefits, but also work with smallholders engaged in subsistence agriculture. There are two reasons to focus some effort on smallholders. First, they are often food-insecure, so working with them is a direct effort to improve food security. Second, in the aggregate they control a lot of land that the world needs to be more productive. Recognize that extension services may be very important to them. Recognize also that they do not exist in a vacuum, but to increase their contributions they require roads, effective and competitive supply chains and marketing chains, access to capital, a functioning legal system, and other infrastructure.

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