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# ASAS Centennial Paper: Landmark discoveries in swine nutrition in the past century<sup>1,2</sup>

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**ABSTRACT:** During this centennial year of the American Society of Animal Science (ASAS), it is of interest to look back over the history of our Society and, in particular, to the many contributions made by researchers in the area of swine nutrition. A great number of basic and applied research studies involving the nutrition of weanling, growing, and finishing pigs, and gestating and lactating sows have been conducted by swine nutritionists during the past 100 yr. Most of these studies were conducted at universities by animal scientists or by the graduate students under their leadership. Others were conducted by nutritionists in the feed and pharmaceutical industries and government scientists at ARS/USDA research centers. Contributions were also made by animal scientists beyond our borders. Much of the research was published in the *Journal of Animal Science* during its 66 yr of existence. Before the first issue of the journal was published in 1942, some of the earlier studies were reported in the Proceedings of the Annual Meeting of the Society of Animal Production,

the forerunner of ASAS. These research studies have progressively led to a better understanding of the role and utilization of dietary energy, protein, AA, carbohydrates, fats, minerals, and vitamins by pigs and have helped to quantify the nutrient requirements of pigs for various stages of growth, for sows during gestation and lactation, and to a limited extent, for boars. Determining the nutritional value of a wide array of feedstuffs, evaluating feeding strategies, and assessing the value of growth-promoting and carcass-enhancing agents have been important research contributions as well. To identify the particular studies that were among the most instrumental in contributing to our present knowledge of swine nutrition is, to say the least, a daunting assignment. To aid in this task, a survey of swine nutritionists was conducted in which they were asked to identify and rank the 10 most significant findings in swine nutrition during the past 100 yr. The results of that survey are presented in this paper.

**Key words:** century, history, research, swine nutrition

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## EARLY HISTORY OF OUR SOCIETY

The American Society of Animal Science (ASAS) has a rich heritage. During this centennial year, it is interesting to look back to the beginnings of our professional society and see how it has progressed through the past 100 yr.

On July 28, 1908, a group of animal nutritionists from 13 state agricultural experiment stations and the USDA met during a summer school session at Cornell University, Ithaca, New York, and formed a permanent organization involved with animal nutrition research

(Anonymous, 1910). Later that year, on November 26, 1908, the group met with other interested persons at the International Livestock Exposition in Chicago and formed the American Society of Animal Nutrition. This new society consisted of 33 charter members from 17 state experiment stations, the USDA, and Canada. Professor H. P. Armsby from Pennsylvania State University was elected as president of the new organization.

A year later on November 27 to 29, 1909, the first professional papers were presented at the Livestock Exposition Hall in Chicago by some of the leaders of the new organization. At the business meeting, it was reported that the Society had grown to 100 members during the first year. At the time, the annual membership dues were \$2.00 and the balance in the treasury at the time of the meeting was \$17.85 (Anonymous, 1910). Another important item of business was a vote by the members to publish the proceedings of the annual meeting. President Armsby gave the first president's

<sup>1</sup>Invited centennial paper at the Annual Joint Meeting of the American Society of Animal Science and the American Dairy Science Association, July 7 to 11, 2008, Indianapolis, Indiana.

<sup>2</sup>Appreciation is extended to the 66 animal nutritionists who participated in the survey that is summarized in this paper.

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annual address. An important concern expressed in his address was whether the food supply would be sufficient for the future population of the United States. Armsby's message included a challenge to the members to make more efficient use of energy and byproducts, to be responsible for teaching and conducting research to meeting the future food supply, and to acknowledge the need for broad and comprehensive research investigations (Anonymous, 1910).

In 1915, the name of the Society was changed from the American Society of Animal Nutrition to the American Society of Animal Production. The constitution was amended to allow membership to those interested in teaching, breeding, and management investigations, as well as nutritionists. At that time, there were 114 members. Forty-six years later, in 1961, a second name change was approved by the membership, to the American Society of Animal Science.

Annual meetings were held in Chicago, Illinois, until 1962 except for a 5-yr period from 1915 to 1919 when the annual meeting was held on college campuses. From 1963 to 1988, the annual meetings were held on university campuses. The first meeting at a convention site was in Lexington, Kentucky, in 1989; then after returning to university campuses for the following 2 yr, a permanent move to convention sites occurred in 1992 and continues until the present time.

## CHANGES IN AGRICULTURE

It should not be a surprise to anyone that agriculture has made dramatic changes during the past century. The changes in acreage, yield, and price of 2 major crops fed to swine and other livestock provide an excellent example. According to the 1910 US Census of Agriculture (1912), farmers in the United States produced 2.55 billion bushels (64.8 million t) of corn from 98.4 million acres (39.8 million ha) of crop land for an average yield of 26 bushels/acre (1.63 t/ha). The corn in 1908 was valued at \$0.56/bushel (\$22/t), 10 to 12 times less than the current price of corn. In 2008, it was estimated that approximately 80 million acres (32.4 million ha) of corn will produce 12.3 billion bushels (312.7 million t), with a yield of 154 bushels/acre (9.68 t/ha) (NASS, 2008). Introduction of new technologies (especially the discovery of hybrid corn) has contributed to the tremendous increases in yield.

With respect to soybeans, this crop was not even listed in the 1910 Census of Agriculture. The small amount of soybeans that may have existed at the turn of the century was grown for a green manure crop or as forage for cattle (Drackley, 2000). The pioneering research with soybeans by George Washington Carver at Tuskegee Institute opened new avenues for usage of soybeans as a source of protein and oil rather than simply for use as a forage. Now, 100 yr later, it is estimated that 73 million acres (29.5 million ha) of crop land in the United States will produce approximately 2.97 billion bushels (80.9 million t) of soybeans, with a yield

of 40.5 bushels/acre (2.73 t/ha; NASS, 2008). Soybean production has made tremendous growth in the past 50 to 60 yr because of its value as an oil source for humans and the widespread use of soybean meal as a high-quality protein source for livestock and poultry.

The animal industry has changed also. In 1910, there were 6.36 million farms in the United States, with an average size of 146 acres (59.1 ha) per farm (US Census of Agriculture, 1912). In 2000, the number of farms decreased to 2.13 million with an average of 441 acres (178 ha) per farm (US Census of Agriculture, 2002). Total pig inventory was about the same in 1910 as in 2000 (58.2 vs. 60.4 million), but the number of farms that produced swine decreased from 4.35 million in 1910 to 78.9 thousand in 2000, a 55-fold decrease. Interestingly, 68.4% of all farms raised swine in 1910, whereas in 2000, only 3.7% of all farms were classified as producing swine. In contrast, the number of hogs per farm has increased nearly 60-fold during the past century, from 13 hogs per farm in 1910 to 756 hogs per farm in 2000. The trend of fewer farms and more production per farm is not unique to swine production; it has also occurred in poultry, dairy cattle, beef cattle, and other segments of animal production.

## WHAT WAS KNOWN ABOUT PIG NUTRITION A CENTURY AGO

H. C. Dawson, a Poland China breeder, authored *The Hog Book* in 1911 and wrote of his experience of 50 yr in the practical handling of swine in the American Corn Belt (Dawson, 1911). In his book, Dawson cited a survey that he conducted of experiment stations asking for details of the "best and most economical rations for hogs." From 20 responses, he concluded the following. For weanling pigs, all respondents stressed good pasture—alfalfa, clover, or rape. Corn, legume pasture, and water were listed by respondents from the Corn Belt states. Corn, skim milk, and shorts were listed by those from states where dairying was important, and tankage was suggested if milk was unavailable. Barley and ground soybeans were mentioned by a few respondents. Slop feeding was consistently mentioned, and wood ashes, charcoal, and salt were also recommended.

Another reference that illustrates what was known about swine nutrition 100 yr ago is the eighth edition of the well-known textbook, *Feeds and Feeding* (Henry, 1908). Corn, barley, and oats were cited in this book as being useful for fattening swine. Corn meal was said to be superior to whole corn, and wet feeding, soaking, or cooking of grains was cited as being beneficial. It was understood at that time that skim milk, meat scraps, and pasture were important for good performance of pigs. Middlings were cited as being twice as valuable as bran, and potatoes and beets were also listed as possible feedstuffs for pigs. Supplementing the feeding program with ashes from wood or coal, salt, and water was also emphasized in the text book.

In this 1908 reference, some points regarding feeding management included the idea that “shoats should be maintained in open air and sunshine, away from pens and yards, kept on natural earth, and allowed to roam pastures carpeted with bluegrass, alfalfa, clover, or rape.” It was implied that swine should be fed to reach 300 pounds (136 kg) by 1 yr of age. Brood sows were said to need clover or alfalfa hay, meals rich in protein, and plenty of exercise. Interestingly, it was recognized that certain feeds would produce poor flavor in pork whereas other feeds produced soft, oily fat. Even at that time in our history, it was implied that consumers were demanding leaner pork. Tables in this 1908 reference book listed the composition (water, protein, ether extract, crude fiber, ash, and nitrogen-free extract) of over 200 feedstuffs along with digestibility coefficients (based on ruminant studies) for each.

The first papers published in the Proceedings of the American Society of Animal Production in 1914 to 1917 also provide insight on the state of the art of swine nutrition at the beginning of the 20th century (Anonymous, 1914, 1915, 1917). John Evvard from Iowa State University published a paper titled “The Corn Problem in Swine Feeding” in which he discussed the insufficient level and quality of protein in corn. In 2 other papers, Evvard discussed the “free-choice” system of feeding swine and emphasized that pigs could balance their diets adequately if allowed to consume corn and tankage on a free-choice basis. A paper by Forbes (Ohio State University) presented information from mineral metabolism experiments, and a paper by Hart and McCollum (University of Wisconsin) presented information on the feeding of strictly vegetable diets on growth and reproduction of swine. Cottonseed meal was reported to be unsatisfactory as a protein source for swine (Burns, Texas A&M University), and different preparations of corn for hogs of different sizes was presented by King (Purdue University).

Based on these nearly 100-yr-old references, it seems that there was a certain level of basic understanding about how pigs should be fed in the early 1900s. However, most of the knowledge at that time was based on what was known about individual feedstuffs, combinations of feedstuffs, and general observations based on practical experience of pig feeding. Very little was known about individual nutrients, and many of the nutrients now known had not yet been discovered. Undoubtedly, tremendous progress has been made in understanding the major and finer points of swine nutrition during the past 100 yr. Much of this information has been presented at the meetings of ASAS as well as published in the 86 volumes of the *Journal of Animal Science* since its inaugural issue in 1942.

## MAJOR DISCOVERIES IN SWINE NUTRITION

Numerous important discoveries in swine nutrition have been made by animal scientists during the past century and many have shaped where we are today. To

identify all of the important discoveries and to categorize them according to their significance is a daunting and almost impossible task. Obviously, it is difficult to completely eliminate biases because anyone (including myself) who has devoted their life to this profession has personal feelings about the importance of their own research areas.

Several sources were used to help identify important areas of discovery in swine nutrition during the past century. Hanson (1958) prepared an excellent review of the first 50 yr of progress in swine nutrition from 1908 to 1958. Similar reviews were prepared by Baker and Speer (1983) on protein-amino acids, Seerley and Ewan (1983) on energy, and Miller and Kornegay (1983) on mineral and vitamin nutrition at the 75th anniversary of ASAS. Other reviews were prepared by Wahlstrom (1983) and Baker (2003).

To obtain additional opinions of important discoveries and to help avoid personal biases of the author, a survey was conducted in the spring of 2008. The survey was mailed to 100 swine nutritionists in academia ( $n = 72$ ) and industry ( $n = 28$ ). Some of the surveys were sent to nutritionists who were early in their careers, some were mid-career or late-career nutritionists, and some of the nutritionists had retired. The survey asked for an opinion of the 10 most significant landmark discoveries in swine nutrition during the past 100 yr. In addition, the recipients were asked to either rank their responses from 1 to 10 (with 1 being the most important) or to group them into top third, middle third, and bottom third. Additional discoveries (more than 10) could also be listed. Of the 100 surveys sent, 66 replies were received (a 66% response rate), with 48 from academia and 18 from industry. The greatest response rate was from retirees (75%, 15 of 20).

As expected, responses varied from very broad answers (e.g., the discovery, synthesis, and determination of requirements of AA, vitamins, and minerals) to very specific ones (e.g., discovery of the animal protein factor, vitamin B<sub>12</sub>). Some responses dealt with management issues (e.g., the move to confinement and slatted floors, development of the self-feeder). As expected, some areas of discovery were listed by many responders, whereas others were listed by a very few (in some cases, only 1 or 2 responders).

Based on the opinions of the 66 nutritionists who responded to the survey, the opinions of those who reviewed the initial 50 and 75 yr of our Society (Hanson, 1958; Baker and Speer, 1983; Miller and Kornegay, 1983; Seerley and Ewan, 1983; Wahlstrom, 1983), and the opinions of this author, the more significant swine nutrition discoveries during the past century are placed (in no particular order) into the following 12 categories. A short discussion of some of these discoveries follows.

### Energy

The development of the energy systems for swine is certainly one of the major research accomplishments in

swine nutrition. A century ago, very little was known about the energy content of feeds or the energy requirements of swine for maintenance, growth, reproduction, and lactation. Energy values were initially determined from the chemical composition of feedstuffs (CP, crude fiber, ether extract, nitrogen-free extract) and the digestibility of these components as determined in digestibility studies with ruminants, and the energy values were expressed as TDN. The development of the bomb calorimeter enabled researchers to determine the energy content of feeds and feces and brought about a more precise method of determining the DE of feedstuffs; yet, for many years DE was simply calculated from TDN using equations. In 1965, Diggs et al. (1965) published a classic paper in the *Journal of Animal Science* on the DE and ME of feedstuffs commonly used in pig feeding. Over the next 20 to 30 yr, research in the laboratories of Richard Ewan at Iowa State University, Jean Noblet in France, and others greatly expanded the knowledge base on the DE, ME, and NE of feedstuffs (DeGoey and Ewan, 1975; Noblet and Henry, 1993).

Energy requirements for maintenance, growth, pregnancy, and lactation have been established and are summarized in the 10th edition of Nutrient Requirements of Swine (NRC, 1998). Numerous studies also have established relationships (i.e., ratios) between the energy content of diets and requirements for protein and individual AA (particularly Lys).

Although fat was recognized to be a concentrated energy source long before 1908, its benefit as a dietary addition for pigs on rate and efficiency of growth was documented by many researchers in the latter part of the past century. Of particular importance was the finding that supplemental fat is of greater benefit in a hot versus moderate or cold environments because of its low heat increment (Stahly and Cromwell, 1979). The studies of Seerley et al. (1974) and others demonstrated that fat supplementation during late gestation and lactation improves BW at birth in pigs and milk production in sows, resulting in improved weaning weights in pigs, as reviewed by Pettigrew (1981).

The early finding that certain long-chain PUFA were required by pigs (Witz and Beeson, 1951) and the later finding that the pig could synthesize its EFA requirements from a dietary source of linoleic acid (Kass et al., 1975) were important discoveries.

### **Protein and AA**

One of the major discoveries in the first half of the past century was the recognition that all protein sources were not the same. Certain protein sources were found to be nutritionally superior to other sources; hence, the concept of "protein quality" was born. An example is the early studies of Osborne and Mendel (1914) with rats and later with pigs, which clearly showed that zein (the major protein in corn) was an extremely poor source of protein that would not support growth. Later, it was found that the inferior quality of zein protein was

due to its extremely low content of Lys and Trp. The concept of protein quality became more apparent as more information became available on the AA profile of proteins in feedstuffs. Obviously, the advent of the AA analyzer played a key role in bringing about and clarifying this understanding.

Following the discovery of the individual AA and identification of their structures, chemical synthesis became possible. The availability of crystalline AA led to the classic studies of W. C. Rose and associates at the University of Illinois with rats and chicks that identified which AA were essential (indispensable) and nonessential (dispensable) in the diet, and the establishment of dietary requirements for these species (Rose, 1938). Early research on establishment of AA requirements with pigs was accomplished in the laboratories of J. K. Loosli at Cornell University, W. M. Beeson at Purdue University, and D. E. Becker at the University of Illinois (Lewis, 2001). Since those early pioneering studies, a tremendous amount of research on AA nutrition of pigs has been conducted by many swine nutritionists. The explosion of research in this area during the past 40 to 50 yr is attributed to the availability of relatively inexpensive AA (especially Lys, Met, Thr, and Trp, due to improved production technology) for research studies.

In 1950, the National Research Council (NRC) first listed estimated requirements for 3 AA—Lys, Met, and Trp—in their second edition (NRC, 1950; Table 1). Requirement estimates of the other 7 essential AA were published by the NRC in 1953 (NRC, 1953); however, they were only listed for young pigs from 11 to 32 kg of BW. It was not until 1968 (sixth edition; NRC, 1968) that the NRC published AA requirements for gestating and lactating sows and gilts. Studies at the University of Illinois (initially by Rippel et al., 1965; Rippel, 1967) and Iowa State University (Lewis and Speer, 1973) were instrumental in establishing the AA requirements for sows. An important finding at that time was the discovery that Arg was not essential for sows (Easter et al., 1974). The NRC first listed AA requirements for finishing pigs in their seventh edition (NRC, 1973); AA requirements for boars were not listed until the ninth edition of NRC (1988).

The initial studies at the University of Kentucky by Stahly et al. (1988) that pigs with a high lean growth potential required more dietary Lys than pigs with low lean growth rates stimulated a great deal of research interest among other swine nutritionists in re-evaluating the Lys requirement of modern genotypes. Stahly's laboratory also conducted numerous studies that assessed the effect of high-health pigs on their Lys requirement (Williams et al., 1997).

The development of ileal cannulation procedures by Canadian researchers (Cunningham et al., 1962) and the implementation of this technology by researchers in Europe and at Texas A&M University (Easter and Tanksley, 1973) led to many research studies that quantified the apparent and true digestible AA in feedstuffs

**Table 1.** Nutrients listed in the National Research Council (NRC) publication, *Nutrient Requirements of Swine*, from the first to tenth edition<sup>1,2</sup>

| Edition | Year | Pages,<br>No. | References,<br>No. | Nutrients | Nutrients with an estimated requirement   |
|---------|------|---------------|--------------------|-----------|---|
| 1       | 1944 | 10            | 69                 | 11        | TDN, CP, Ca, P, K, carotene, vitamin A, vitamin D, thiamine, niacin, pantothenic acid, riboflavin, pyridoxine   |
| 2       | 1950 | 19            | 137                | 14        | Added: Lys, Trp, Met, Cl<br>Deleted: K, vitamin A   |
| 3       | 1953 | 28            | 175                | 27        | Added: choline, vitamin B <sub>12</sub> , Cu, Fe, I, Mn, Arg, His, Ile, Leu, Phe, Thr, Val  |
| 4       | 1959 | 34            | 227                | 29        | Added: DE (calculated from TDN), vitamin A, Mg, Zn  |
| 5       | 1964 | 40            | 533                | 30        | Added: Se   |
| 6       | 1968 | 69            | 333                | 30        | Changed: carotene to $\beta$ -carotene  |
| 7       | 1973 | 56            | 421                | 31        | Added: DE (not calculated from TDN), ME, vitamin E  |
| 8       | 1979 | 52            | 749                | 35        | Added: K, vitamin K, biotin, folacin  |
| 9       | 1988 | 93            | 1,151              | 36        | Added: available P, linoleic acid<br>Changed: niacin to available niacin  |
| 10      | 1998 | 189           | 1,524              | 36        | Added: true and apparent ileal digestible AA, Cr recognized as a required nutrient<br>Changed: AA and energy requirements estimated with mathematical equations (model) |

<sup>1</sup>NRC (1944, 1950, 1953, 1959, 1964, 1968, 1973, 1979, 1988, 1998).

<sup>2</sup>With respect to AA requirements, Lys, Met, and Trp were first listed for pigs (23 to 113 kg of BW) in the second edition. Requirements for most or all AA were first listed for weanling and growing pigs (11 to 32 kg) in the third edition; for early-weaned pigs (2.2 to 4.5 kg) in the fourth edition; for bred sows and gilts in the sixth edition; for finishing pigs (35 to 100 kg) and lactating gilts and sows in the seventh edition, and adult boars in the ninth edition.

for swine. Also, the classic studies by Wang and Fuller (1989) at the Rowett Research Institute (Aberdeen, Scotland) and Chung and Baker (1992) at the University of Illinois led to the wide acceptance in the swine industry of the “ideal protein” or “ideal amino acid” concept in which AA requirements are expressed as a percentage of the Lys requirement. The combination of these 2 important discoveries—ideal protein and ileal digestible AA—is widely accepted and used by the feed industry in diet formulation for swine. A review of the bioavailability and digestibility of AA in pig feed ingredients was recently published by Stein et al. (2007).

New and improved technologies have resulted in the commercial production of several AA (Lys, Met, Thr, Trp) that can now economically replace some of the supplemental protein sources while maintaining growth performance and resulting in less N excretion (and in some cases, less odor) in the manure (Carter et al., 1996; Turner et al., 1996; Sutton et al., 1999).

## Minerals

Some of the initial discoveries in mineral nutrition in the past century involved the identification of the roles of Ca, P, and salt for pigs. One of the early pioneers in swine nutrition, John Evvard at Iowa State University, developed a mineral mix that was widely used in the 1920s; it was based on salt (which he called “white gold”), limestone, spent bone black (residue of charred bone used as a decolorizing agent in the sugar refining industry), and potassium iodide (Speer, 1990). This was followed by discoveries of the roles and essentiality of the other major minerals and the trace elements along with the establishment of their requirements.

More studies have been conducted with swine on Ca and especially P in the past 50 yr than for any of the

other major minerals. The use of bone ash and bone breaking strength as response criteria that are very sensitive to Ca and P adequacy has played a major role in helping researchers establish the Ca and P requirements of pigs (review by Cromwell, 2005).

One of the early discoveries in the trace mineral area was that goiter and the birth of hairless pigs could be prevented with I supplementation (Hart and Steenbock, 1920). The role of Zn as a means of preventing parakeratosis lesions was discovered in the 1950s. This mineral deficiency became quite evident as soybean meal (which is high in phytic acid) became popular and replaced animal protein sources (Tucker and Salmon, 1955; Lewis et al., 1956). Also, the interrelationship of Zn and Ca was established at about this time. Iron became increasingly important when the industry moved from farrowing pigs in outside pens to inside quarters on concrete floors where pigs rapidly developed Fe-deficiency anemia from not having access to the soil. The development of injectable Fe complexes to prevent anemia occurred because of this (Barber et al., 1955; McDonald et al., 1955; Ullrey et al., 1959). Also, studies at the University of Illinois (Harmon et al., 1967) and elsewhere identified sources of oral iron that were highly available (e.g., Fe sulfate, Fe ammonium citrate) and those that were poorly available (Fe oxide) for young pigs.

The discovery that small amounts of Se were essential and that it was not simply a toxic mineral was one of the more important discoveries of the past century (Eggert et al., 1957). This mineral was found to be an important component of glutathione peroxidase, an enzyme that protects against peroxidative damage to cells (Rotruck et al., 1973). The interrelationship of Se and vitamin E also was also a significant discovery of this past century, as reviewed by Oldfield (2003). Numerous studies by Don Mahan’s group at The Ohio State

University greatly increased the knowledge base of both organic and inorganic Se nutrition of swine (Mahan, 1985).

For many years, little was known about the bioavailability of many of the minerals, especially those in commonly used feedstuffs such as cereal grains, oilseed meals, and byproduct feeds. The development of the slope-ratio procedure for determining the relative bioavailability of P in feedstuffs based on bone strength and ash was first reported in our laboratory at the University of Kentucky (Cromwell, 1979). That information is now known for a large number of feedstuffs (Cromwell, 1992; Cromwell and Coffey, 1993), and the feed industry now routinely formulates their feed on an available P basis. Other information on bioavailability of trace minerals (oxides vs. sulfates vs. organic forms) has also been elucidated in recent years.

One of the more interesting discoveries in the mineral area was that high levels of Cu, as  $\text{CuSO}_4$ , had growth-stimulating properties when fed to pigs. The discovery of the pharmacological effect of Cu is generally contributed to Braude (1945) in England, but it was actually first reported by Evvard et al. (1928). There was renewed interest in Cu when our group at the University of Kentucky reported that Cu and antibiotics acted independently and that the effects of Cu and antibiotics were additive (Stahly et al., 1980). Studies demonstrated that some forms of Cu (sulfate, carbonate, chloride) are effective as growth stimulants, whereas other forms (sulfide, oxide) are ineffective (Cromwell, 1997; Cromwell et al., 1998).

An increased concentration of Zn, as  $\text{ZnO}$ , was initially reported by Danish researchers to reduce the incidence of diarrhea (Poulsen, 1989), and subsequent work in the United States by Hahn and Baker (1993) and other researchers has shown that pharmacological levels of  $\text{ZnO}$  also stimulate growth in early-weaned pigs. High levels of Zn, Cu, or both are now commonly used in starter diets for weanling pigs. The role of Cr as a glucose tolerance factor was discovered in the late 1950s by Klaus Schwarz and Walter Mertz (NRC, 1997), and its dietary essentiality for pigs was established 10 yr ago (NRC, 1998).

## Vitamins

Numerous deficiency disorders such as scurvy, beriberi, night blindness, and xerophthalmia were described as early as 2,600 to 1,500 BC, and rickets was described in the second century AD, but nutritional means of preventing these conditions was not discovered until many centuries later (McDowell, 1989). In the 1890s, Christian Eijkman discovered that beriberi (now known to be thiamin deficiency) was associated with the feeding of polished rice and that it could be prevented by feeding whole grain rice or by adding rice polishings back into the diet. The Polish biochemist Casimir Funk coined the name "vitamine" representing "vital amine" to describe this N-bearing accessory food factor. Later,

other essential factors in food were discovered, and although most of them did not contain N in their structure, the class of nutrients retained the name that was shortened to "vitamin."

Vitamin A was another one of the first vitamins discovered (McCollum and Davis, 1913) and its structure was elucidated in 1931. This group was also responsible for differentiating the vitamins into the fat- and water-soluble categories.

Important discoveries of the role, essentiality, and synthesis of most of the vitamins occurred during the late 1920s and 1930s. The rat and chick played major roles in these discoveries, but research work with pigs soon followed and important discoveries were made. Early findings that "necro" or "necrotic enteritis" in pigs (symptoms similar to pellagra in humans) was preventable with certain B-complex vitamin (niacin, riboflavin) supplementation and that locomotor disorders of the hindquarters (goose-stepping) were preventable with pantothenic acid additions were important discoveries (McDowell, 1989).

Research studies showed that vitamins A, D, E, and many of the B-complex vitamins became especially important when the industry moved into confinement facilities and pigs no longer had access to legume pasture, sunlight, and other sources of vitamins. Also, the move to confinement on fully slatted floors—and particularly when sows were placed in stalls—prevented animals from coming into contact with their feces making it necessary to fortify diets with B-complex vitamins and vitamin K, vitamins that are synthesized by enteric microbes. Numerous research studies led to the establishment of requirements for these vitamins in confinement-reared pigs.

The antioxidant properties of, and requirements for, vitamin E along with its relationship with Se were discovered during this past century. The possible need for supplemental vitamin K and vitamin C in certain instances were reported by some researchers. It was also discovered that niacin in cereal grains and biotin in wheat and sorghum were unavailable or poorly available to pigs (Luce et al., 1967; Anderson et al., 1978; Kornegay, 1986). Studies with sows showed that litter size and other measures of reproductive performance could be enhanced with supplementation of choline (NCR-42 Committee on Swine Nutrition, 1980), biotin (Lewis et al., 1991), and folic acid (Bryant et al., 1985; Lindemann and Kornegay, 1989) to corn-soybean meal diets. The identification of the active form of vitamin D (1,25-dihydroxy cholecalciferol) at the University of Wisconsin by Hector DeLuca's group was another important discovery (Lund and DeLuca, 1966; Holick et al., 1971; Schnoes and DeLuca, 1980).

Most nutritionists agree that the 1948 discovery of vitamin  $\text{B}_{12}$ , the last of the vitamins identified, by Merck scientists (Rickes et al., 1948) and a few weeks later by an English group (Fantes et al., 1949), had more impact on the swine industry than any of the other vitamin discoveries. For many years, it was well known that

there was some unidentified growth factor (now known to be vitamin B<sub>12</sub>) in animal protein sources, and that growth in pigs and chicks was impaired if they were fed all-plant diets without the inclusion of fish meal, meat meal, or other animal protein source. What made this discovery so important was 2-fold—it subsequently allowed the successful feeding of simplified corn-soybean meal diets to swine and poultry, and it was closely associated with the discovery of an important antibiotic, chlortetracycline, and its growth-promoting effects for swine.

### ***Antimicrobial Agents and Other Feed Additives***

The discovery of the growth-promoting properties of antibiotics was one of the more important discoveries of the past century. This discovery was made when researchers were in the process of establishing the vitamin B<sub>12</sub> activity in a fermentation media and observed that growth rate of chicks was considerably greater than could be attributed to the amount of vitamin B<sub>12</sub> present in the media (Stokstad et al., 1949). Similar growth responses from fermentation media were subsequently demonstrated in studies with pigs (Cunha et al., 1949; Jukes et al., 1950; Lepley et al., 1950; Luecke et al., 1950). Stokstad and Jukes (1949) identified the agent in their original fermentation media as the antibiotic chlortetracycline.

Within a few years, numerous papers were published and the advent of subtherapeutic use of antibiotics became well established as the swine industry rapidly adopted the use of antibiotics in diets for swine. Other antimicrobial agents were later discovered and several of them were cleared by the Food and Drug Administration (FDA) for use in swine feeds. Some nutritionists would argue that the use of feed-grade antibiotics in feeds has given a greater return to swine producers per amount invested than any other dietary item. Presently, there is pressure by some groups to eliminate the use of subtherapeutic antibiotics in animal feeds because of the concern of transferable resistance and other public health concerns, many of which have been shown to be unfounded (Hays, 1977; CAST, 1981; IOM, 1988; NRC, 1999).

Certain organic acids, when added to starter diets, were discovered to improve growth in young pigs (Kirchgeßner and Roth, 1982; Giesting and Easter, 1985). Numerous supplements that alter the microbial populations in the gut, commonly called probiotics (e.g., *Lactobacillus acidophilus*, *Streptococcus faecium*, *Saccharomyces cerevisiae*) or prebiotics (e.g., fructooligosaccharides) have been evaluated by many researchers, but they have not consistently been observed to enhance growth performance of pigs (Cromwell, 2001).

Numerous enzyme supplements have been tested in recent years and some combinations have been shown to improve digestibility of certain types of feeds, par-

ticularly those that are high in fiber. One of the most significant developments in the enzyme area was the discovery and subsequent commercial production and use of phytase as a means of reducing the amount of inorganic P supplementation needed in the diet and thus reducing the amount of P excreted in the manure (Jongbloed et al., 1992; Cromwell et al., 1993b). The advent of recombinant DNA technology and other biotechnology techniques such as cloning has made phytase a practical and economical feed additive.

### ***Metabolic Modifiers***

Several repartitioning agents that modify carcass composition in swine and other animals were discovered in the past century. The  $\beta$ -adrenergic agonists such as cimaterol, clenbuterol, and ractopamine were observed to improve carcass leanness along with improving rate and efficiency of growth (Jones et al., 1985; Anderson et al., 1987; Watkins et al., 1990). Ractopamine (trade name Paylean; Elanco Animal Health; Greenfield, IN) is the only one of these products that has been cleared by the FDA for use in finishing swine in the United States.

Another repartitioning agent that was discovered in the 1970s was porcine (p) ST, commonly referred to as pGH (Machlin, 1972). Studies at several universities showed that carcass leanness was dramatically increased when pST was administered intramuscularly on a daily basis (Chung et al., 1985; Evock et al., 1988). Although bovine ST was approved by the FDA for use in dairy cattle, pST has not been cleared in the United States for swine. However, pST is cleared for use in swine in some other countries (e.g., Australia, Mexico).

### ***Feeding Management***

One of the early discoveries during the past century was the finding by Evvard that pigs would do a reasonable job of balancing their diets if provided a self-feeder with separate compartments for grain and protein supplement. While this practice was widely accepted for many years, eventually self-feeding of complete-mixed diets became more popular as knowledge emerged regarding the levels of nutrients required for various stages of growth. Phase feeding and split-sex feeding became popular as AA requirements for barrows vs. gilts became more clearly defined (Cromwell et al., 1993a). Information gained from research studies elucidated the impact of fineness of grind, quantification of particle size of feeds, and the value of pelleting of diets for swine (Jensen and Becker, 1965; Wondra et al., 1995).

### ***Diets for Early-Weaned Pigs***

Pigs in 1908 were farrowed outdoors and weaned at 10 to 12 wk of age. Gradually, weaning age decreased

to 8 wk, then to 6 wk, 4 wk, and more recently to 2 to 3 wk of age. The ability to successfully wean pigs at this early age can be attributed to the development of superior diets along with excellent facilities that met the environmental needs of the young pig. Obviously, early weaning of pigs enables producers to rebreed sows earlier and increases the number of litters per year.

Complex diets containing substantial amounts of milk products were developed in the 1950s as researchers learned more about the digestive enzyme development in the neonatal pig and the ability of the pig to utilize various sources of carbohydrate, fat, and protein. Some of the early studies with early weaned pigs were done by research groups at Iowa State University and the University of Illinois who discovered that pigs utilized lactose, milk fat, and milk proteins well shortly after birth but did not utilize starch, maltose, or sucrose very well until they were several weeks of age (Becker and Terrill, 1954; Becker et al., 1954; Kitts et al., 1956; Hartman et al., 1961). Fructose was also found by these groups to be poorly utilized by very young pigs. These early discoveries paved the way toward the development of diets that are commonly used today—diets that are high in dried whey or crystalline lactose for early-weaned pigs.

The discovery of the nutritional aspects of spray-dried porcine plasma by the Iowa State University group in the 1980s was an important discovery (Gatnau et al., 1989). Spray-dried porcine plasma, an excellent source of immunoglobulins, was investigated by many research groups and found to prevent the postweaning growth check that commonly occurred in early-weaned pigs (review by Coffey and Cromwell, 2001). Interestingly, whether the dried plasma was of bovine or porcine origin had no effect on its nutritional properties. This product is widely used today during the initial 1 to 2 wk postweaning, especially when pigs are weaned at 3 wk of age or less. Dried animal blood cells, an excellent source of Lys, is also widely used in starter diets. Because blood cells are extremely deficient in Ile, the elevated concentrations of Leu and Val relative to Ile can potentially result in some branched-chain AA antagonism; thus, blood cells should be used in limited amounts in pig diets or the diets must be supplemented with Ile (Parr et al., 2003; Kerr et al., 2004).

Other specialty ingredients sometimes used in starter diets whose nutritional properties have been evaluated include fish meal and blood meal. Improved drying methods discovered years ago prevent destruction of Lys and other AA and, therefore, contribute to an improvement in the bioavailability of Lys and other AA in blood meal (Parsons et al., 1985).

### ***Other Feed Ingredients***

One of the most significant changes in swine nutrition during the past century was the technology that led to the adaptation of soybean meal as a major protein

source for swine and poultry. As indicated previously, soybeans were a relatively unknown commodity at the beginning of the 20th century, and crushing operations (on a small scale) did not begin until about 1920. An event that boosted the use of soybeans was World War II. Before the war, the United States imported nearly one-half of its edible fats and oil. At the advent of the war, edible oil supplies to the United States were cut, so processors and users turned to soybean oil. Also, the increased demand for meat and meat products during the war was a contributing factor to an increased use of alternative protein sources in foods and feeds. However, soy oil was not widely accepted in the United States for human use because of its strong odor and flavor that was associated with its vulnerability to rapid peroxidation. The discovery that citric acid could be used to bind trace-metal prooxidant catalysts (an earlier discovery by German scientists that was recorded by American scientists at the end of World War II), the switch from steel storage and processing equipment to stainless steel, and the development of solvent processing to more efficiently remove the oil and produce a higher quality meal with less heat-damaged protein all contributed to the rapid expansion of the soybean industry in the 1940s (Baker, 2003). Finally, the discovery of vitamin B<sub>12</sub> in 1948 paved the way for the wide acceptance of the vitamin- and mineral-fortified corn-soybean meal diet for swine. These discoveries resulted in a tremendous expansion of the soybean industry in the United States.

The discovery of high-lysine corn at Purdue University in the 1960s was thought at the time to be one of the most significant discoveries of the century because of its potential impact on the nutrition of both animals and humans. Mertz et al. (1964) discovered that the mutant *opaque-2* gene in corn resulted in substitution of some of the low-quality zein protein with higher quality proteins (primarily glutelin) in the endosperm. The initial studies with pigs showed that *opaque-2* corn was nutritionally superior, and diets containing *opaque-2* corn required less soybean meal than diets containing conventional corn (Cromwell et al., 1967). Other mutant genes in corn were subsequently identified (*floury-2*, *sugary-2*, *waxy*) that also had improved nutritional properties. Unfortunately, these types of corn did not live up to their initial expectations because of agronomic problems such as reduced yields and greater susceptibility to diseases due to the softer endosperm. Nevertheless, the important finding that the composition of corn and other cereal grains could be altered by mutant genes and later by genetic engineering techniques resulted in seed companies taking on new directions in their breeding programs. Furthermore, it opened the door for a unique collaborative role between plant breeders and animal nutritionists that still exists today (Cromwell, 2000).

Implementation of biotechnology to produce genetically modified plants with improved agronomic or nu-

tritional traits continued during the past 20 yr and hold promise for the future. Low-phytate corn (Spencer et al., 2000), low-phytate soybean meal (Cromwell et al., 2000), and high free-lysine corn (Anderson, 1998) are among some of the recent discoveries that have been researched with pigs.

Numerous byproduct feeds have been studied during the past century and many are now being used in swine diets. The evaluation of alternative energy and protein feedstuffs will continue to be an active research area, especially when corn and soybean meal are unusually costly, as they are at the present time. Distillers dried grains with solubles (**DDGS**) is a particularly attractive byproduct, as reviewed by Stein (2007), because of its abundance resulting from the expansion of the fuel ethanol industry.

A byproduct that was commonly used in swine diets (especially sow diets) during the mid-1900s following the move to confinement rearing was dehydrated alfalfa meal (**dehy**). This product was not only a rich source of  $\beta$ -carotene and other vitamins, but was also thought to provide other unidentified factors (Fairbanks et al., 1945). Although dehy had its place in the early years, after supplemental Se began in the 1970s and vitamin K soon after (due to a hemorrhagic problem in Nebraska caused by feeding moldy corn and correctable with vitamin K or dehy supplementation; Baker et al., 1974a,b), there was no longer need to use dehy in swine diets, thus resulting in its demise.

### ***Feeding Programs for Gestating and Lactating Sows***

Sow feeding has seen many changes during the past century. In the past, sows were fed considerably more energy and higher protein diets compared with modern feeding practices. The finding by several research groups that 2 kg/d of a fortified corn-soy diet produced more desirable gestational BW gains compared with considerably higher feeding levels was a significant discovery (Baker et al., 1969). The findings in the 1970s that decreased protein levels had little effect on litter size compared with previously recommended protein levels was also important. In fact, some studies showed that sows could be fed extremely low protein levels during gestation without affecting litter size or pig weights, but it had a dramatic negative effect on milk production during the subsequent lactation period and on return to estrus (Pond et al., 1963; DeGeeter et al., 1972, 1973).

Several important discoveries regarding nutrition of the lactating sow were made in the past 20 yr, including the fact that prolific sows nursing large litters need elevated levels of dietary protein to maximize milk production, prevent excessive BW loss during even a relatively short lactation period, and prevent delayed return to estrus following weaning of litters (Stahly et al., 1990).

### ***Establishment and Fine-Tuning of Nutrient Requirements***

A general area of discovery this past century (and already mentioned in previous sections) has been the establishment and refinement of the pig and sow requirements for AA, minerals, and vitamins. The NRC of the National Academy of Science has played a key role in defining nutrient requirements for all stages of production as new research has emerged. The NRC was established in 1916 as an independent organization to provide advice to the federal government on issues of science and technology. The first of 10 editions of *Nutrient Requirements of Swine* was published in 1944 when the nation was at war (NRC, 1944).

An overview of the 10 editions of this publication (NRC, 1944, 1950, 1953, 1959, 1964, 1968, 1973, 1979, 1988, 1998) gives an indication of which nutrients were well defined with respect to their requirements and how new information generated by research groups affected the changes during the period from 1944 (first edition) to 1998 when the 10th edition was published. Table 1 shows those nutrients for which a requirement was listed for growing pigs during this period. This table also shows the number of pages and the number of references cited in the 10 editions of the publications that covered a 54-yr period. The increase in numbers of pages and references illustrates the growth in the knowledge base of swine nutrition during the latter part of the past century.

An important development that occurred in the past 20 to 30 yr was the generation of information by numerous researchers that allowed for the development of mathematical models to estimate nutrient requirements. The pioneering work in the 1970s and 1980s of John Black (CSIRO, Australia) and Colin Whittemore (University of Edinburgh) in developing pig growth models to simulate accretion of whole body components resulting from various nutritional and environmental inputs was an important contribution to pig nutrition (Miller and Calvert, 2001). Models enable one to refine nutrient requirements based on the genetic capacity of a particular genotype, the environment in which the pig resides, the sex of the pig, the number of pigs that a sow is nursing, the milk production of the sow, and other factors. A growth model in the most recent edition of the NRC (1998) uses equations to partition energy and AA requirements for maintenance and lean growth rate of growing-finishing pig. In addition, sow models in the NRC publication employ equations to estimate energy and AA requirements for maintenance, potential litter size, number of pigs nursed, and BW change during lactation.

### ***Instrumentation and Other Technologies***

The development and availability of ion exchange chromatography for AA analysis was a major step for-

**Table 2.** Survey results—top 20 research areas as ranked by the total score of the survey responders

| Rank | Discovery area  | Score <sup>1</sup> | % <sup>2</sup> |
|------|---|--------------------|----------------|
| 1    | Amino acids—discovery, synthesis, requirements                | 673                | 87             |
| 2    | Nutrient requirements—establishment, refinement               | 532                | 68             |
| 3    | Vitamins—discovery, synthesis, requirements                   | 381                | 67             |
| 4    | Minerals—discovery, role, requirements                        | 347                | 56             |
| 5    | Antibiotics—discovery of growth enhancement                   | 231                | 64             |
| 6    | Nursery diets for early weaned pigs, whey, lactose, plasma    | 219                | 55             |
| 7    | Nutrient bioavailability—P, trace elements                    | 187                | 46             |
| 8    | Ideal protein concept   | 180                | 46             |
| 9    | Phytase   | 158                | 50             |
| 10   | Soybean meal and the corn-soybean meal diet                   | 137                | 38             |
| 11   | Crystalline AA synthesis                                      | 136                | 38             |
| 12   | Discovery and synthesis of vitamin B <sub>12</sub>            | 128                | 27             |
| 13   | Metabolic modifiers—ractopamine                               | 99                 | 36             |
| 14   | Ileal digestibility of AA                                     | 88                 | 24             |
| 15   | National Research Council requirements, development of models | 81                 | 18             |
| 16   | Sow diets—gestation and lactation                             | 80                 | 27             |
| 17   | Phase feeding and split-sex feeding                           | 78                 | 26             |
| 18   | Selenium requirements, interrelationship with vitamin E       | 76                 | 21             |
| 19   | Copper sulfate and zinc oxide as growth stimulants            | 73                 | 24             |
| 20   | Development of energy systems                                 | 69                 | 18             |

<sup>1</sup>The first choice by a responder to the survey was given a 10, a second choice was given a 9, a third choice was given an 8, and so on.

<sup>2</sup>Percentage of the 66 responders to the survey who listed this discovery area in their top 10.

ward in improving estimates of requirements and composition of feeds in the area of AA nutrition. Similarly, atomic absorption spectrophotometry did the same for mineral analysis. Near-infrared spectroscopy and other sophisticated lab analysis have played major roles in increasing the knowledge base in animal nutrition.

The development of large databases for nutrient composition of feedstuffs and software for linear programming in least-cost diet formulation have been tremendous aids to nutritionists. Additionally, the development of desktop computers, software for word processing, spreadsheets, and statistical analysis (e.g., SAS software) for rapid data analysis, and electronic technology that accommodates Internet searches has greatly aided swine nutritionists and their graduate students in their research programs.

### RANK OF IMPORTANCE OF DISCOVERY AREAS AS DETERMINED FROM THE SURVEY

Although I have attempted to describe many of the important research areas in this paper, a ranking of these areas in their order of importance was one of the objectives of this review. To produce a ranking of the discovery areas that were cited by the 66 nutritionists who responded to the survey, the following procedure was implemented. If the participants submitted a numerical ranking to their list of discoveries, a score of 10 was given to their top choice, and scores of 9, 8, 7, 6, 5, 4, 3, 2, and 1 were given to their second through tenth choices, respectively. If the responders chose to rank their discovery areas into 3 groups, a score of 7 was given to each discovery area in the top third, a score of 5 was given to each area in the middle third, and a

score of 3 to each area listed in the bottom third. If responders chose to not rank their top 10 discovery areas, a score of 5 was given to each choice. Any responses in excess of the top 10 were each given a score of 1. The number of responders who listed a discovery area in their top 10 (expressed as a percentage of all responders), the total points for each discovery area (number of responders multiplied by their score), and the average scores were calculated for each discovery area.

Table 2 shows the ranking of the top 20 discovery areas based on the total scores as well as the percentage of responders who listed these discovery areas in their top 10 choices. Not surprising, the discovery, synthesis, and establishment and refinement of requirements for AA, vitamins, and minerals were in the top 4 rankings, and were listed in the top 10 by more than one-half of all responders. The AA category ranked highest and was listed in the top 10 by 87% of the responders.

The discovery of antibiotics was ranked high as were discoveries of specialty ingredients, particularly dried whey, lactose, and dried animal plasma, that enhanced the development of diets for early-weaned pigs. Discoveries of the bioavailability of P and trace minerals, development and acceptance of the ideal protein concept, and new technologies that brought about the use of phytase in diets ranked in the top 10 as well as discoveries leading to the establishment of soybean meal as the leading protein supplement for swine and the widespread acceptance of the fortified, corn-soybean meal diet. Most of these discoveries were listed in the top 10 by approximately one-half or more of the survey participants.

Areas of discovery that were in the second tier of 10, shown in Table 2, included the synthesis of crystalline amino acids, discovery of vitamin B<sub>12</sub>, metabolic

**Table 3.** Survey results—rank of discovery areas based on the average score of those who responded to a specific research area

| Rank | Discovery area  | Average score |
|------|---|---------------|
| 1    | Corn-soybean meal diet  | 7.2           |
| 2    | Discovery and synthesis of vitamin B <sub>12</sub>            | 7.1           |
| 3    | Vitamins—discovery, synthesis, requirements                   | 6.9           |
| 4    | National Research Council requirements, development of models | 6.8           |
| 5    | Ideal protein concept   | 6.0           |
| 6    | Nutrient requirements—establishment, refinement               | 5.9           |
| 7    | Development of energy systems                                 | 5.8           |
| 8    | AA—discovery, synthesis, requirements                         | 5.7           |
| 9    | Soybean meal  | 5.6           |
| 10   | Ileal digestibility of AA                                     | 5.5           |
| 10   | Antibiotics—discovery of growth enhancement                   | 5.5           |
| 10   | Nutrient bioavailability—P, trace elements                    | 5.5           |

modifiers, ileal digestibility of AA, establishment of the NRC and use of models to estimate requirements, sow feeding systems, phase feeding and split-sex feeding, selenium, CuSO<sub>4</sub> and ZnO as growth stimulants for weanling pigs, and development of energy systems.

Interestingly, the discovery order changed when the average score was assessed for responders who listed specific discovery areas in their top 10, as shown in Table 3. Discoveries leading to the adaptation and widespread use of the soybean meal diet, along with the discovery of vitamin B<sub>12</sub> and other vitamins ranked the highest with average scores of 7.2 to 6.9. Establishment of nutrient requirements, including modeling, the ideal protein concept, development of energy systems, AA discoveries and digestibility, discovery of antibiotics, and establishment of nutrient bioavailability all received average scores of 5.5 or greater++ when they were ranked in the respondents' top 10.

## SUMMARY AND CONCLUSIONS

A reasonable summary of the subject of the landmark studies in swine nutrition over the past century would be to list those areas cited by L. E. Hanson in his summary of the first 50 yr of swine nutrition (Hanson, 1958), and then supplement this list with additional discoveries based on the results of the survey along with my experience gained from being involved in swine nutrition research for the past 41 yr. Eleven major discovery areas based on Hanson's summary (in bold) and my additions are as follows (they are in no particular order):

1. **The recognition of "quality" in protein, which has led to reasonably satisfactory estimates of the amino acid content of feedstuffs and requirements of young pigs.** The establishment of AA requirements for all BW and classes of swine, including finishing pigs, and gestating and lactating sows, on both a total dietary AA basis and an ileal digestible AA basis. The synthesis and use of crystalline AA in diets to reduce N excretion, and the concept of

"AA balance" and "ideal protein" in diet formulation.

2. **The development of the soybean crop from insignificant proportions to the major source of high quality protein for swine rations.** The continued and widespread acceptance of the fortified corn-soy diet for growing-finishing swine and gestating-lactating sows. A better understanding of the nutritional value of byproduct feeds that can be used in swine feeds when economically feasible.
3. **Studies in mineral nutrition and especially the determination of Ca and P requirements; the solution of Fe-deficiency anemia and goiter.** Further advances in trace mineral nutrition, especially with respect to Zn and Se. The determination of mineral bioavailability (especially P and trace minerals) in feedstuffs and mineral sources.
4. **The discovery of vitamins, their isolation and synthesis, and studies that led to estimates of requirements of pigs; the commercial development of low cost vitamin supplements.** Continued assessment of vitamin requirements for growth, reproduction, and lactation. The move to confinement rearing of pigs on fully slatted floors and the feeding of all-plant diets contributed to an increased need for B-complex vitamin and vitamin K fortification of diets.
5. **The discovery of value of antibiotics and other antibacterial agents.** The discovery of pharmacological levels of dietary copper sulfate and zinc oxide as growth stimulants in weanling pigs and of ractopamine and other  $\beta$ -adrenergic agonists, and porcine ST for carcass improvement in finishing pigs.
6. **Changes in methods of feeding from self-feeding (free-choice grain and supplement) to complete mixed diets, shift from pasture to dry lot, and early weaning of pigs.** Even earlier weaning made possible with specialty ingredients such as dried whey, lactose, and

- spray-dried plasma in starter diets. Shift to confinement rearing of growing-finishing swine, slatted floors, hot nurseries, and total confinement of sow herd. Adoption of phase feeding and split-sex feeding practices, and better understanding of feed processing on nutrient utilization.
7. Development of energy systems; determination of DE, ME, and NE of feedstuffs and establishment of DE, ME, and NE requirements for maintenance, growth, gestation, and lactation.
8. Discovery of genetically improved grains, oilseeds, and other feedstuffs.
9. Development and acceptance of phytase to reduce P excretion.
10. Fine tuning of nutrient requirements by the NRC including the use of mathematical models to estimate requirements based on genotype (lean growth rate, sow productivity), environment, and other factors.
11. Advancement in technology in laboratory instrumentation, data processing, and communications.

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