Midwest Swine Nutrition Conference Proceedings

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Midwest Swine Nutrition Conference

Schedule of Presentations

8:15 am	Registration
9:00	Welcome and Introductions *Dr. Merlin Lindemann, University of Kentucky*
9:05	Deliver the Promise: Design for the Next Generation of Agricultural Scientist Leaders *Dr. Bobby Moser, Vice President and Dean Emeritus, The Ohio State University*
9:50	A New Approach in Determining the Micromineral Needs of the Growing Pig *Dr. Don Mahan, The Ohio State University*
10:20	Break
10:50	Nutritional Value of Soybean Products *Dr. Hans Stein, University of Illinois*
11:25	Soybean Meal and the Immune Response to PRRS Virus *Dr. Ryan Dilger, University of Illinois*
12:00	Lunch
1:00 pm	Nutritional and Functional Properties of Fiber in Swine Diets *Dr. Knud Erik Bach Knudsen, Aarhus University, Denmark*
1:45	Effect of Decreasing Net Energy in Grow-Finish Diets With or Without Paylean *Dr. Brian Richert, Purdue University*
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2:45	Switching Feed Ingredients In/Out of Grow-Finish Diets *Dr. Dale Rozeboom, Michigan State University*
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Deliver the Promise: Design for the Next Generation of Agricultural Scientist Leaders

Bobby D. Moser
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"We cannot predict the future, but we can create it."

- Jim Collins, *Great By Choice (2011)*

Introduction

There is an implied "promise" to students that if they receive an undergraduate or graduate degree from our university, they will be well-prepared to enter the workforce with the necessary knowledge and leadership skills to be successful. The question is: are we delivering on that "promise" now and will we in the future?

The original intent of the land-grant university system to enhance the quality of life and serve as an economic engine remains relevant in today's rapidly changing world. The manner in which the students of the future learn, though, is vastly different from that of our past, and it is imperative that the system of higher education continuously revolutionize the content, skills and methods in which information is delivered to ensure we can deliver on that "promise" to our students.

The Land-Grant University

Before changes to student preparedness are considered, it is important to first envision what the land-grant university of the future might look like.

As we celebrate the 100th anniversary of the Smith Lever Act and more than 152 and 127 years of the Morrill and Hatch Acts, respectively, we recognize and acknowledge the tremendous success of the land-grant university's commitment to teaching, research and extension, and its global impact. The land-grant university gives students an opportunity to see the "big picture" with broader experiences, and successfully bring basic and applied science together.

While the food and agricultural system in the United States is one of the most robust and progressive in the world, most people in the U.S. take for granted the quality, abundant availability, safety/security, and affordability of our food and water. This generation of students needs to see and understand the complexities of the total food and agricultural system, since they will soon be responsible for determining how 9 billion people by 2050 can be sustainably fed. The food and agricultural industry anticipates hiring more agricultural graduates, but the concern is if there will be enough graduates to fill those positions. According to the Bureau of Labor Statistics, in 2011 there were 52,000 job opportunities in the food and agricultural industry, with only 49,300 available graduates. The university is challenged with fulfilling those needs with quality, workforce-ready graduates.

Looking forward, changes will be needed in the structure and funding sources of the land-grant university system to be viable and successful in delivering on the "promise" to our students.

Structural questions to thoughtfully consider are:

- Will there be campuses?
- Will there be classrooms?
- Will there be residence halls?
- Will there even be colleges of agriculture?

The **funding** of the land-grant university has traditionally relied on support from state, federal and local entities in addition to student tuition. Today, in addition to this support, the university is becoming more reliant on additional funding from endowments, grants and contracts.

Questions for consideration are:

- How will the land-grant university be funded in the future?
- Will the privatization of the public university be the new operational model?
- Will the traditional funding sources be sufficient and available in the future, or will more creative ways to generate revenue be necessary?

At Ohio State, a "One University" initiative emphasizes interdisciplinary partnerships across campus, as well as external collaborations with other universities and industry, including Centers of Excellence. This concept shakes up our traditional classroom instruction model, and forces us to consider the future structure and funding of the land-grant university.

Student Preparedness

It has been suggested that the university should measure success not only upon the student's entry-value upon admission, but equally consider the student's value-added knowledge and experience at the time of graduation. In addition to the curriculum materials necessary to earn a degree, employers tell us that our graduates are well-trained in the sciences, but more than ever, need to be prepared to think creatively, communicate, innovate, access, evaluate and integrate knowledge, and work collaboratively in teams.

A 2011 joint study between Michigan State University and the Association of Public and Land-Grant Universities (APLU) was conducted to identify important proficiencies needed for successful transition to competitive employment in food, agriculture, natural resources and related careers. Interestingly, employers and alumni ranked the "soft skills" higher than, or as important as, discipline knowledge—faculty and students' perspectives were reversed. Provided below in rank order are the seven "soft skills" identified:

1. Communication Skills. In addition to the ability to communicate accurately, concisely, pleasantly and professionally both orally and in writing, effective listening skills are important.

2. Decision Making/Problem Solving Skills. It is advantageous to be able to identify and analyze problems, find creative and innovative solutions, and implement ideas.

3. Self-Management Skills. Employers are looking for individuals with efficient and effective work habits, well developed-ethic, integrity, and loyalty characteristics, and a sense of urgency to address and complete tasks.

4. Team Skills. Most desirable is a productive team member with a positive and encouraging attitude, is punctual and meets deadlines, and is aware and sensitive to diversity.

5. Professional Skills. The abilities to build and maintain effective relationships with colleagues, customers, businesses and the public are essential, as are the capacities to accept and apply critique and direction, and be trustworthy with sensitive information.

6. Experience. Employers are specifically looking for work-related internships, international/study abroad experiences, and those who have had opportunities to develop teamwork, leadership and project management skills.

7. Leadership Skills. Thinking strategically, seeing the "big picture," and recognizing when to lead and when to follow are key leadership skills.

Additional skills employers brought to my attention for graduate and undergraduate students are:

- The awareness of how consumer preferences will impact how food is produced, processed and marketed, which will significantly influence how and what the university researches and teaches.
- The commitment to being a life-long learner.
- Adaptability to societal and economic changes in their own community and throughout the world.
- The value of undergraduate research.

Skills specifically suggested for graduate students include opportunities for internships where they could strengthen their knowledge of and experience with industry, teaching and/or extension. At present, the Ph.D. degree is considered to be research-based, even though many doctoral students find their way into academia where there are expectations of teaching and/or extension in addition to research responsibilities. As a result, more graduate students are finding their way into industry; thus opportunities and experiences to learn about teaching, extension and industry merit consideration.

Method of Delivery

In order to most effectively communicate with and educate today's students, higher education must embrace a new paradigm. E-Learning has opened up classroom instruction to the world, and technology usage is the new normal. A recent student survey revealed that Google is considered by many to be one of the best inventions ever, and is a student's first option for seeking knowledge. The land-grant university system must quickly identify how we can use technology and social media for not only teaching, but to disseminate research-based information, as well. Students today are driven by instant gratification and share that they prefer a mix of learning environments, and that resources have three to 8 seconds to catch their attention.

The generation born since 1980 makes up more than one-third of the labor force, and that will undoubtedly increase exponentially when the youngest baby boomers hit retirement age. This group, the Millennials, will soon be our industry leaders. More diverse than pre-

ceding generations, Millennials have been raised to embrace differences and pursue discovery, and they have learned to work and learn in more collaborative environments. It is the responsibility of the land-grant university to make deep cultural changes to accommodate different values—on life-long learning, motivation, hierarchy, changing demographics and work/life integration.

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A New Approach in Determining the Micromineral Needs of the Growing Pig

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Summary

Two experiments were conducted with weanling and grower-finisher pigs to evaluate the effect of graded levels of Cu, Fe, Mn and Zn (relative to published NRC mineral requirements) on several biological measurements. The diets were comprised of conventional feed ingredients with added phytase and with Paylean added during the last 3 weeks of the trial. The results indicated that at or above 50% of the NRC (1998, 2012) requirements, there was no further benefit on pig performance measures (gains or feed intakes), hematology measurements, liver and duodenal metallothionein, or the activity of the hepatic antioxidant enzymes (Cu/Zn SOD, Mn SOD, GSH-Px), nor did it affect the liver concentration of these minerals with the exception of Zn during the grower-finisher period. These results indicate that the current NRC micromineral requirement levels are in excess of the pig's requirement. We suggest that future mineral requirements be expressed on a "digestible mineral" basis.

Introduction

The NRC committee routinely publishes, approximately every 10 years, a revision of the nutritional requirements for swine. These requirements have examined the scientific literature and publish their evaluations from these research studies. The relevance of most of the published literature to the NRC is good but questionable in the mineral area. The major reasons for this conclusion are as follows:

- The genetics of today's pigs are leaner and faster growing than pigs in previous years (Wiseman et al., 2009).
- Muscle tissue retains minerals and with leaner pigs with more total muscle, they retain more minerals (Wiseman and Mahan, 2010).
- Pigs that grow faster metabolize more nutrients and more demand is placed on the antioxidant enzymes.
- Pigs are being weaned from 18 to 21 days and have less carry-over from the sow.
- Grower-finisher pigs are marketed earlier and at a heavier weight, thus increasing the mineral requirements.
- Feeds are more effectively processed thus resulting in better digestibility.
- Facilities have greatly improved and are more environmentally controlled.

Other more current factors need to be considered in today's swine industry and research programs.

- The use of exogenous enzymes, like phytase, is now widely used and can be important in the release of innate minerals. Most of the previous studies did not use the enzymes.
- The bioavailability of minerals in feed components has always been a limiting factor in diet formulation and has generally been ignored.
- Some of the minerals when provided in excess of the requirement may act as pro-oxidants.

The current and previous NRC (1998, 2012) mineral requirements presented in Table 1 demonstrate few differences between the two publications for the past 15 years. The exception is Se. However, the values from 1998 also encompass the total contribution from feed ingredients (including the innate microminerals); whereas, the 2012 NRC requirements indicate that the innate minerals should be considered as "safety factors". Regardless, almost no one fortifies the diet with the NRC mineral levels, but rather most trace mineral premixes exceed the requirement.

If one calculates the innate micromineral content of conventional diets using feed ingredients commonly used in today's modern pig diets, we find that in most cases, the total microminerals provided exceed the NRC requirements except for Zn, Se and I (Table 1). However,

this calculation assumes 100% bioavailability of these innate minerals. It should be noted that the macromineral sources used in many diets (e.g., dicalcium phosphate and limestone) contain high levels of Fe and Mn (NRC, 2012) that contribute toward their high innate levels in the final diet mixtures.

Although the bioavailability or digestibility of various trace mineral sources and feedstuffs are not known, a recent study by Jolliff and Mahan (2013) indicated that the digestibility of the minerals (macro and innate microminerals) in grower pigs should not be ignored in diet formulation. A summary of their results presented in Table 2 indicated that Ca and P levels can affect Ca and micromineral digestibility. These results confirm that the macrominerals could chelate and reduce the digestibility and availability of trace minerals. Perhaps most important is the finding that when the basal diet did not contain a trace mineral supplement, the innate microminerals had an average of 44% digestibility, and when the higher Ca and P were provided, the average digestibility of the innate microminerals in the basal diet declined to 38%. This study also demonstrated increased bioavailability from organic sources and an improved digestibility of Mn and Se between organic and inorganic minerals (Table 3).

Experimental Design

Given the above factors, we designed two experiments to evaluate the micromineral needs (except Se and I) of weanling and grower-finisher pigs. The diets were conventional diets containing feeds commonly used in the industry. The innate mineral content of each diet mixture is presented in the lower half of Table 1. All diets included phytase because of its demonstrated improved utilization of the microminerals (Adeola et al., 1995; Jolliff and Mahan, 2012). During the final 3 weeks of the grower-finisher experiment, Paylean was included in order to enhance lean production and potentially the pig's need for microminerals.

In order to better understand the efficacy of the innate microminerals and their role in swine diets, a basal nonfortified micromineral diet was fed in each experiment. Because we did not know the balance of minerals that would optimize the various parameters to be measured, we used the NRC (1998) added as a percentage of the NRC (1998) requirement to the diets and added the premix at graded levels. In the weanling pig trial (experiment 1) we used both organic (Bioplexes) minerals and inorganic mineral salts, whereas in the grower-finisher experiment, we used only the organic microminerals. This design differs from other studies in that the minerals were added as a "package" and does not allow the evaluation of each mineral independently; it is the combination of minerals that we felt was important in our design. Further description of the grower-finisher experiment is described by Gowanlock et al. (2013). Because the microminerals are involved in several biological functions, we attempted to evaluate and report on each biological role below. The experimental results are reported by measurement criteria, not by experiment in order to better understand their impact on the pig.

Results

Performance

In experiment 1 (weanling pigs), the addition of Cu, Fe, Mn, and Zn to the diet had no effect on daily gains during the initial 21 days postweaning (Table 4). From 21 to 35 days postweaning there was a numerical increase in daily gains to the 25% NRC treatment level, but this was not significant. There was no further improvement in pig gains to the higher levels of microminerals. These results indicate that during the initial period postweaning, the carry-over from the sow or the bioavailability of the innate minerals from the basal diet was sufficient to meet the performance needs of the weaned pig. However, after 21 days postweaning, there was a trend toward an improvement in pig gains. This agrees with the results of Martin et al. (2011) and Hill et al. (2014) demonstrating that additional Zn (i.e., 75 mg Zn/kg diet) was necessary to attain maximum growth rate in rapid growing weanling pigs. These results further demonstrate that the pig can utilize the innate dietary microminerals and that the NRC levels as listed (1998, 2012) are perhaps in excess when conventional diets are fed during the nursery period.

The growth rate during the grower-finisher period in experiment 2 was excellent as pigs grew rapidly reaching a market weight of 115 kg in slightly less than 5 months of age, and there was no effect from the added trace minerals on feed intake or feed efficiency (Table 5). There was no effect of added microminerals beyond that of the basal diet for each production phase. During the latter period when Paylean was added to all diets, there was no mineral level effect on pig performance. These results indicate that the availability of the innate microminerals in the basal diet was adequate to meet the growth requirement of the grower-finisher pig and that additional microminerals were not needed. Although carcass measurements are not included in this report, Gowanlock et al. (2013) demonstrated no difference in the various carcass measurements collected or in pork quality from the various mineral treatment groups.

Blood Hematology

The young pig has a very rapid growth rate and its tissues have a large need for nutrients and oxygen for biological functions. The oxygen is provided from hemoglobin (Hb) and Fe is a vital component of this molecule. Injected Fe in the neonatal pig is necessary to prevent anemia, but current research indicates this is not adequate for the latter part of the postweaning period in rapidly growing pigs. The rapidly growing pig has a greater requirement for tissue growth and oxygen than pigs of previous generations (Hill et al., 1999; Jolliff and Mahan, 2011). The results of experiment 1 from weanling pigs indicated that Hb and hematocrit (Hct) were lower on 21 day postweaning when the basal diet was fed (Table 6). This decline in Hb response has been previously demonstrated, but both Hb and Hct increased thereafter to 35 days postweaning. Although the 7- and 14-day values did not differ significantly from the other mineral groups on these dates, their lowering values imply that Fe may have limited Hb production. When the supplemental mineral levels were provided, there was no further increase in Hb or Hct values above the 25% supplemental NRC level.

Trace mineral levels seemed to have a minimal effect on hematological measures in grower-finisher pigs (Table 7). In experiment 2, there were no differences in Hb or Hct values at any production phase from any treatment group (Table 7) indicating that the levels of Fe in the basal diets were adequate for the market pig.

Metallothionein and Liver Antioxidant Enzymes

Zinc is transferred across the duodenum and is bound subsequently in the liver by the protein metallothionein. Carlson et al. (1999) demonstrated the affinity of this protein for Zn, but other microminerals may also be bound by this protein. Liver is the major site where metallothionein is found for Zn retention. This protein also binds Zn in the intestinal mucosa but much smaller amounts are present in the jejunum.

In experiment 1, a pig was killed at 10 days and another at 35 days postweaning. At day 10, there was no difference in the liver metallothionein from the NRC levels fed (Table 8). However, it is clear that the duodenum had an increasing content of this protein to the 50% NRC treatment level. This indicates that the duodenum was active in the transport and absorption of Zn. In contrast, there was less metallothionein in the jejunum on day 10 indicating that its role in Zn absorption is minimal. These results indicate that the carry-over response from the sow may have had an effect at day 10, whereas at 35 days postweaning the liver had more metallothionein and was greater as the NRC dietary mineral levels increased to the 50% NRC level. The duodenum again had a greater concentration than the jejunum but there was no treatment response. These results indicate that liver was retaining the microminerals (most probably Zn) and demonstrate that the duodenum was more active than the jejunum.

The microminerals Cu, Mn, Zn, and Se are all involved in critical biological functions largely as components of the antioxidant enzymes. The enzymes Cu/Zn superoxide dismutase (SOD) and glutathione peroxide (GSH-Px) containing Se are intracellular antioxidant enzymes, whereas Mn SOD is an extracellular antioxidant enzyme. In experiment 1, these enzymes were not affected by increased supplementation at 10 or 35 days postweaning by the mineral levels provided. The activity of the Cu/Zn SOD and GSH-Px enzymes were greater than Mn SOD. These results indicate that either the carry-over from the sow was adequate to meet the pig's needs or that the innate minerals from the basal diets were adequate to meet these needs.

These liver antioxidant enzymes were largely unaffected by the dietary treatments in grower-finisher pigs (Table 9).

Liver Mineral Concentrations

When microminerals are absorbed from the gut, they are used by the body for biological functions, stored in tissues, or excreted. When the animal's requirement for a specific micromineral is met, it is assumed that its concentration in the tissue plateaus with excesses excreted. Historically, the liver has been considered as the main storage organ in the body for several trace minerals. However, the mineral concentrations in the weanling pig liver plateaued and was unaffected by treatment mineral level (Table 10). When increasing consumption of the minerals had been fed, there was no increase in liver minerals. This was true at both 10 and 35 days postweaning.

In experiment 2 with grower-finisher pigs, the minerals were also unaffected by the various treatments except for Zn (Table 11; $P < 0.05$). Liver Zn continued to increase as the dietary NRC levels increased. This result is consistent with the increasing metallothionein during the grower-finisher period. This indicates that either the requirement for Zn was not met or that the liver was storing Zn beyond the pig's requirement.

Generally we have indicated that the liver does not appear to be just a major storage organ for the microminerals, except possibly for Zn. The minerals retained in the liver do appear to be adequate to meet the pig's requirements. The liver probably excretes the excess when fed above the requirement level rather than store

Table 1. Mineral requirements of growing pigs and the calculated innate content of conventional diets at each production phase (NRC, 2012).

	Weight range, kg (NRC, 2012)						
	5 - 7 kg	7 - 11 kg	11 - 25 kg	25 - 50 kg	50 - 75 kg	75 - 100 kg	100 - 135 kg
Item	**NRC requirements (1998[1], 2012[2])[3]**						
Ca, %	0.90 (0.85)	0.80	0.70	0.60 (0.66)	0.5 (0.59)	0.52	0.46
P, %	0.70	0.65	0.60	0.50 (0.56)	0.45 (0.52)	0.40 (0.47)	0.43
Cu, mg/kg	6.0	6.0	5.0	4.0	3.5	2.0 (3.0)	2.0
Fe, mg/kg	100	100	80 (100)	60	50	50 (40)	40
Mn, mg/kg	4.0	4.0	3.0	2.0	2.0	2.0	2.0
Se, mg/kg	0.30	0.30	0.25	0.15 (0.20)	0.15	0.15	0.15
Zn, mg/kg	100	100	100 (80)	60	50	50	50
	Dietary mineral composition from innate ingredients						
	C-SBM-DW-FM-PP-Dical-Lime[4]			**C-SBM-Dical-Lime[5]**			
	3 - 5 kg	**5 - 10 kg**	**10 - 20 kg**	**20 - 50 kg**	**50 - 80 kg**	**80 - 120 kg**	**80 - 120 kg (+paylean)**
Ca, %	0.79	0.80	0.80	0.81	0.81	0.70	0.70
P, %	0.63	0.60	0.65	0.65	0.59	0.55	0.55
Cu, mg/kg	7	8	8	8	7	7	7
Fe, mg/kg	125	139	150	223	207	182	182
Mn, mg/kg	12	14	16	18	17	18	18
Se, mg/kg	0.3	0.3	0.3	0.3	0.3	0.3	0.3
Zn, mg/kg	26	29	30	27	26	25	25

[1] The 1998 NRC states (page 110): For minerals and vitamins, the requirements include the amounts of these nutrients that are provided by feed ingredients.
[2] The 2012 NRC states (page 209): Levels of supplementation of trace minerals or vitamins may be at or above estimated requirements and any amounts supplied by feed ingredients then contribute to the margin of safety.
[3] Values listed in each column are NRC (1998) requirements, while those in parenthesis are 2012 NRC requirements when they differ from 1998 requirements. Weight ranges between the two NRC requirements may differ.
[4] Mineral containing feedstuffs: C-SBM-DW-FM- PP-Dical-Lime reflects corn, soybean meal, dried whey, fish meal, plasma protein, dicalcium phosphate, and limestone, respectively.
[5] Mineral containing feedstuffs: C-SBM-Dical-Lime reflects corn, soybean meal, dicalcium phosphate, and limestone, respectively.

them. Thus the liver serves as an organ to process and transport minerals to the appropriate tissues.

What Does All This Mean?

There are several important points in this paper that perhaps we need to better understand on how we look at the micromineral requirements for growing swine.

1. The past and current NRC (1998, 2012) listed dietary requirements for swine appear to be in excess of what needs to be added to the pig's diet containing phytase and ractopamine, particularly for the grower-finisher pig.
2. Several measurement parameters have indicated that performance, hematology, tissue mineral concentrations, and the hepatic antioxidant enzymes containing these microminerals were not affected when dietary micromineral levels were below listed NRC requirements.
3. Although the innate microminerals were previously ignored in diet formulations, research now indicates that this needs to be more seriously considered in establishing mineral requirements.
4. Liver does not accumulate the microminerals as feed consumption increases. Although pigs were consuming an increasing amount of minerals as treatment levels increase, there was no concurrent increase in liver minerals. An exception would be when pharmacological levels of some minerals are fed (e.g., Cu, Zn) and their liver contents would be expected to be substantially greater.

Microminerals are needed for the immune system, and this was not accounted for in these experiments The pigs in this experiment would be considered healthy and fast growing. Under such conditions, our results would indicate that adding a trace mineral premix at 50% of the NRC (2012) requirement would be sufficient to meet their needs and also perhaps for stressful situations. Because of the recognition that the innate minerals are important in meeting at least part of the pigs mineral requirements, the use of "digestible minerals" would seem to be better than the current method of using total or recognizing them as "safety factors".

Table 2. Effects of Ca and P level and form of Cu, Fe, Mn, Se, and Zn on total tract apparent digestibility of minerals in grower pigs.

		Basal + No TM			Basal + Inorganic TM			Basal + Organic TM		
Mineral	Ca:P level,%:	0.65:0.55	1.00:0.85	SEM	P-value	0.65:0.50	1.00:0.85	SEM	P-value	0.65:0.50	1.00:0.85	SEM	P-value
Macrominerals													
Ca		59.1	56.9	3.09	0.65	61.3	56.9	2.52	0.18	61.6	52.7	2.98	0.07
P		61.4	57.8	1.52	0.23	58.1	60.0	1.64	0.57	60.9	58.6	2.04	0.59
Mg		52.3	47.2	1.55	0.13	47.5	48.1	2.00	0.87	52.1	45.3	2.38	0.18
K		85.9	84.9	0.67	0.43	85.9	84.8	0.67	0.44	85.5	85.3	0.45	0.74
S		85.6	82.8	0.45	0.01	82.1	79.8	0.54	0.05	82.9	79.4	0.57	0.01
Avg.		68.9	65.9	-	-	67.0	65.9	-	-	68.6	64.3	-	-
Microminerals													
Cu		45.4	43.3	2.36	0.55	16.8	18.4	2.53	0.70	25.6	18.9	3.21	0.26
Fe		38.6	36.0	5.14	0.66	28.2	30.1	3.97	0.61	40.4	33.2	4.08	0.16
Mn		25.4	18.0	2.07	0.08	12.3	15.8	2.52	0.50	26.9	14.5	3.05	0.08
Se		78.7	75.9	3.75	0.66	74.0	73.8	2.74	0.97	77.0	78.1	2.10	0.49
Zn		34.3	16.2	3.39	0.02	14.6	17.7	2.33	0.44	21.7	15.4	3.02	0.28
Avg.		44.5	37.9	-	-	29.2	31.2	-	-	38.3	32.0	-	-

Table 3. Comparison of organic and inorganic trace mineral digestibility in grower pigs.

Mineral	Inorganic TM	Organic TM	SEM	P value
Ca, %	59.1	57.2	3.1	0.49
P, %	59	59.7	2	0.78
Cu, %	17.6	22.1	3.2	0.20
Fe, %	29.3	36.8	5.1	0.03
Mn, %	14.1	20.7	3	0.11
Se, %	73.9	77.5	3.8	0.10
Zn, %	16.2	18.5	3.4	0.50

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Table 4. Effect of dietary Cu, Fe, Mn, and Zn levels and source on weanling pig performance.

			Organic TM			Inorganic TM			
Item	**% of NRC:**	**0**	**25%**	**50%**	**100%**	**25%**	**50%**	**100%**	**SEM**
No of reps		11	11	11	11	11	11	11	
BW, kg									
0 d		6.0	5.9	6.0	5.9	6.0	5.9	6.0	0.1
35 d		21.8	22.2	22.2	22.3	22.1	21.3	21.5	0.4
ADG, g									
0 to 7 d		93	112	67	111	96	55	66	9
7 to 21 d		451	426	429	446	437	399	416	11
21 to 35 d		675	726	717	705	708	717	673	11
0 to 35 d		463	475	461	472	471	453	443	8
ADFI, g/kg									
0 to 35 d		666	651	649	673	664	624	651	12
G:F, g/kg									
0 to 7 d		428	514	350	609	435	289	281	44
0 to 35 d		697	733	712	708	712	718	678	7

Table 5. Effect of dietary Cu, Fe, Mn, and Zn micromineral supplementation on growth performance in grower-finisher pigs.

	Treatments						
	% of NRC[1]			Zn, mg/kg[2]		Fe, mg/kg[2]	
Item	**Basal (0)**	**50**	**100**	**25**	**50**	**50**	**SEM**
No. of replicates	7	7	7	7	7	7	-
No. of pigs	37	37	37	37	37	37	-
Age, birth to market, d	144.2	144.3	143.7	143.9	143.9	143.8	2.9
Initial wt., kg	24.07	24.53	23.93	24.31	24.74	24.61	0.84
Phase I							
BW, kg[3]	54.00	54.73	54.24	55.19	55.70	54.80	1.33
ADG, kg	0.90	0.91	0.91	0.92	0.93	0.91	0.03
ADFI, kg	1.77	1.74	1.81	1.75	1.82	1.75	0.05
G:F	0.51	0.52	0.51	0.53	0.51	0.52	0.01
Phase II							
BW, kg	83.16	84.06	82.44	84.16	86.30	84.09	2.03
ADG, kg	1.11	1.12	1.09	1.11	1.16	1.12	0.04
ADFI, kg	2.82	2.85	3.09	2.82	3.01	2.85	0.11
G:F	0.40	0.39	0.36	0.40	0.39	0.39	0.01
Phase III							
BW, kg	118.22	118.76	116.73	118.81	119.97	117.81	2.51
ADG, kg	1.29	1.26	1.25	1.26	1.22	1.23	0.03
ADFI, kg	3.27	3.40	3.37	3.14	3.27	3.15	0.10
G:F	0.40	0.37	0.37	0.40	0.38	0.39	0.01
Overall performance							
ADG, kg	1.08	1.08	1.07	1.08	1.09	1.07	0.02
ADFI, kg	2.56	2.58	2.68	2.51	2.63	2.52	0.07
G:F	0.42	0.41	0.40	0.43	0.41	0.43	0.01

[1] Percent of NRC (1998) requirements added for Cu, Fe, Mn, and Zn to the various treatments for the 50 to 80 kg pig.
[2] Added to basal diet.
[3] Contrast for the 25 and 50 mg Zn vs. the 50 and 100% NRC treatment ($P < 0.05$).

Table 6. Effect of Cu, Fe, Mn and Zn mineral sources and levels on weanling pig blood hematology.

		Organic TM			Inorganic TM			
% of NRC:	**0**	**25**	**50**	**100**	**25**	**50**	**100**	**SEM**
No. of pigs[1]	21	21	21	21	21	21	21	
Hemoglobin, g/dL								
7 d	11.9	12.2	12.3	12.3	12.6	12.5	12.9	0.1
14 d	10.3	10.7	10.9	11.0	10.5	11.0	11.0	0.1
21 d[2]	10.5	10.9	11.4	11.6	11.2	11.5	11.3	0.1
28 d	11.4	11.7	12.1	12.1	12.0	11.9	11.5	0.1
35 d	11.9	11.8	11.9	12.1	11.8	12.0	11.7	0.1
Hematocrit, %								
7 d	38.7	39.6	39.3	39.4	38.9	39.6	41.0	0.3
14 d	32.4	33.3	34.1	34.1	33.3	34.9	34.1	0.3
21d[2]	34.9	35.9	36.7	37.6	37.1	36.7	36.3	0.3
28d	37.6	37.3	38.3	38.9	38.4	38.4	38.3	0.2
35d	39.2	38.7	38.6	39.6	38.2	39.7	38.2	0.2
Cp x 1000, units/ml								
7 d	124.1	125.3	124.0	121.4	124.3	135.4	133.4	2.9
35 d[2]	112.4	132.2	132.7	139.5	133.0	149.7	137.8	3.1

[1] From 3 pigs in each of 7 reps on d 7, 14, 21, and 28 and from 3 pigs in each of 10 reps on d 35.
[2] The basal (0% added Cu, Zn, Fe, Mn) diet differed ($P < 0.05$) from other treatments.

Table 7. Effect of dietary Cu, Fe, Mn, and Zn micromineral supplementation on hemoglobin and hematocrit values during each phase for grower-finisher pigs.

	Treatments						
	% of NRC[1]			Zn, mg/kg[2]		Fe, mg/kg[2]	
Item	**Basal (0)**	**50**	**100**	**25**	**50**	**50**	**SEM**
Hemoglobin, g/dl							
55 kg BW (Phase I)	13.1	12.3	12.5	12.6	12.5	12.4	0.34
80 kg BW (Phase II)	12.8	12.9	12.5	13.2	13.3	13.3	0.61
115 kg BW (Phase III)	13.4	13.3	13.4	13.4	13.0	13.6	0.37
Avg.	13.1	12.8	12.8	13.1	12.9	13.1	0.25
Hematocrit, %							
55 kg BW (Phase I)	40.3	38.7	39.3	38.7	38.3	39.0	0.64
80 kg BW (Phase II)	39.4	37.8	39.1	39.9	39.9	40.5	1.53
115 kg BW (Phase III)	41.1	42.1	41.6	41.1	40.7	42.6	0.78
Avg.	40.3	39.5	40.0	39.9	39.7	40.1	0.64

[1] Percent of NRC (1998) requirements added for Cu, Fe, Mn, and Zn to the various treatments for the 50 to 80 kg pig.
[2] Added to basal diet.

Table 8. Effect of dietary Cu, Fe, Mn, and Zn levels and sources on liver and small intestine metallothionein and liver antioxidant enzymes in weanling pigs.

		Organic TM			Inorganic TM			
Item	**% of NRC:** **0**	**25**	**50**	**100**	**25**	**50**	**100**	**SEM**
No. of pigs[1]	6	6	6	6	6	6	6	
	10 days postweaning							
Metallothionein, µg/g tissue								
Liver[2,3]	506.7[ab]	640.9[a]	467.4[abc]	513.7[ab]	644.6[a]	368.9[bc]	221.1[c]	42.2
Duodenum	26.2	34.2	34.4	22.1	28.2	25.0	26.9	1.5
Jejunum	10.3	17.2	14.4	11.4	12.4	16.3	12.6	0.8
Liver antioxidant enzymes, U/mg protein[5]								
Cu/Zn SOD	50.4	56.2	49.7	42.3	52.0	53.4	56.9	1.7
Mn SOD	8.1	7.7	6.8	8.3	8.4	7.3	7.0	0.3
GSH-Px	0.55	0.51	0.57	0.52	0.58	0.45	0.44	0.03
	35 days postweaning							
Metallothionein, µg/g tissue								
Liver[2,4]	322.6	268.2	456.1	625.5	324.2	1000.2	891.5	77.4
Duodenum	39.6	32.3	28.8	32.0	29.2	35.0	36.3	1.4
Jejunum	11.2	15.3	14.8	15.2	15.4	17.2	16.0	0.8
Liver antioxidant enzymes, U/mg protein[4,5]								
Cu/Zn SOD	50.1	49.6	48.7	48.9	49.0	48.2	47.5	0.9
Mn SOD	6.4	8.3	6.8	7.5	6.8	7.0	7.1	0.2
GSH-Px	0.59	0.61	0.56	0.49	0.62	0.56	0.56	0.03

[1] Represents the total number of pigs sampled; 3 pigs on d 10 and 3 pigs on d 35.
[2] Means within the same row with different superscripts differ ($P < 0.05$).
[3] Linear decrease ($P < 0.05$) in liver MT concentration as dietary level of inorganic mineral increased.
[4] Linear increase ($P < 0.05$) in liver MT concentration as dietary level of inorganic mineral increased.
[5] U/mg protein is identified as follows: For the SOD enzymes the value represent the amount of enzyme that inhibits 50% of enzyme activity with the activity then expressed on a mg protein basis. The GSH-Px enzyme represents the µmole of GSH-Px oxidized per minute.

Table 9. Effect of dietary Cu, Fe, Mn, and Zn supplementation on liver enzyme activity and metallothionein concentration in the liver and small intestine of grower-finisher pigs at 115 kg BW.

	% of NRC			Zn, mg/kg[2]		Fe, mg/kg[2]	
Item	**Basal (0)**	**50**	**100**	**25**	**50**	**50**	**SEM**
No. of pigs	21	21	21	21	21	21	
Metallothionein, µg/g tissue							
Liver[3]	498.7[a]	693.7[b]	567.3[a,b]	748.6[b]	556.0[a,b]	411.6[a]	69.8
Duodenum[3]	27.2[a]	33.1[a,b]	37.5[b]	42.9[b]	34.7[a.b]	31.6[a,b]	3.7
Jejunum	14.0	13.4	12.7	13.8	13.4	13.9	0.9
Liver enzymes, U/mg protein[1]							
Cu/Zn SOD	50.1	50.8	48.5	49.3	49.3	50.6	0.9
Mn SOD[3]	3.91[a]	4.34[b]	3.89[a,b]	3.68[a]	4.05[a,b]	4.08[a,b]	0.16
GSH-Px	0.86	0.93	0.96	0.93	1.01	1.08	0.05

[1] U/mg protein is identified as follows: For the SOD enzymes the value represent the amount of enzyme that inhibits 50% of enzyme activity with the activity then expressed on a mg protein basis. The GSH-Px enzyme represents the µmole of GSH-Px oxidized per minute.
[2] Added to basal diet.
[3] [a,b]Superscripts within the same row with different letters differ, $P < 0.05$.

Table 10. Effect of Cu, Fe, Mn and Zn mineral sources and levels in weanling pig diets on liver mineral concentrations (dry matter basis).

		Organic TM			Inorganic TM			
Item	**% of NRC:**	**0**	**25**	**50**	**100**	**25**	**50**	**100**	**SEM**
No. of pigs[1]		6	6	6	6	6	6	6	-
		10 days postweaning							
Mineral concentration/g liver									
Ca, mg		0.13	0.14	0.14	0.13	0.14	0.14	0.13	0.01
P, mg		11.2	12.2	11.5	11.4	11.1	11.6	12.1	0.2
Cu, µg		18.0	12.1	16.0	19.3	18.2	17.9	16.6	0.9
Fe, µg		435.1	368.9	390.3	383.2	477.1	476.3	360.9	16.4
Mn, µg		13.2	11.9	11.8	11.3	11.7	11.6	11.8	0.2
Zn, µg		266.5	234.3	231.5	226.2	183.1	296.3	232.8	13.2
		35 days postweaning							
Mineral concentration/g liver									
Ca, mg		0.15	0.15	0.14	0.13	0.14	0.15	0.15	0.01
P, mg		11.4	10.8	10.9	11.4	11.3	10.9	11.4	0.2
Cu, µg		16.6	19.7	13.6	14.6	15.4	26.2	19.0	1.3
Fe, µg		485.4	428.3	438.7	541.0	391.7	532.3	430.0	22.7
Mn, µg		12.1	11.6	11.6	11.7	12.0	11.6	11.8	0.3
Zn, µg		212.9	298.9	204.8	274.3	268.1	318.8	246.0	18.3

[1] Represents the total number of pigs sampled; 3 pigs on d 10 and 3 pigs on d 35.

Table 11. Effect of dietary Cu, Fe, Mn, and Zn supplementation on liver micromineral concentration (dry weight) in grower-finisher pigs at 115 kg BW.

	% of NRC			Zn, mg/kg[1]		Fe,mg/kg[1]	
Item	**Basal (0)**	**50**	**100**	**25**	**50**	**50**	**SEM**
No. of pigs	21	21	21	21	21	21	
Liver wt., g[2]	1670.4[a]	1685.1[a]	1641.1[a]	1683.9[a]	1784.7[b]	1653.2[a]	49.0
Liver, % of BW	1.47	1.47	1.46	1.47	1.53	1.45	0.04
Liver, % DM	28.40	28.20	28.60	28.80	28.60	28.20	0.40
Liver micromineral content, mg							
Cu	10.1	10.0	10.2	10.1	9.5	9.14	0.70
Fe	400.2	379.9	395.8	364.3	397.7	384.8	32.2
Mn	5.46	5.35	5.43	5.24	5.34	5.12	0.27
Zn[2]	123.1[a]	142.2[b]	133.4[a,b]	143.6[b]	135.8[a,b]	115.5[a]	9.15
Se	1.04	1.08	1.02	1.10	1.09	1.03	0.03
Liver micromineral concentration, mg/kg							
Cu	5.95	5.88	6.14	5.79	5.25	5.40	0.34
Fe	236.1	225.0	236.7	210.8	218.8	227.1	17.39
Mn	3.24	3.16	3.25	3.04	2.97	3.03	0.15
Zn[2]	72.1[a]	84.2[b]	79.8[a,b]	84.2[b]	75.4[a,b]	68.6[a]	5.80
Se	0.61	0.64	0.62	0.64	0.61	0.60	0.02

[1] Added to basal diet.
[2] [a,b]Superscripts within in the same row with different letters differ $P < 0.05$.

Nutritional Value of Soybean Products

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Summary

Soybean meal, fermented soybean meal, and enzyme-treated soybean meal are excellent sources of protein, and their amino acid profiles complement that of most cereal grains. The crude protein and amino acids in soybean meal are more digestible compared with the digestibility of crude protein and amino acids in other protein sources, such as corn distillers dried grains with solubles, canola meal, or sunflower meal. However, soybean meal can cause decreased growth performance when fed to weanling pigs, but processing of soybean meal to produce fermented soybean meal or enzyme-treated soybean meal removes antinutritional factors and antigenic proteins, which may mitigate transient hypersensitivity in weanling pigs. Soybean meal contains a large percentage of phytate-bound phosphorus; however, addition of microbial phytase or further processing to produce fermented soybean meal, hydrolyzes the phytate bonds and increase the concentration of free phosphorus in soybean meal. Soybean meal can be included in diets fed to all phases of swine production to supply adequate levels of amino acids; however, conventional soybean meal levels usually are restricted to less than 20% in diets fed to weanling pigs. In contrast, fermented soybean meal and enzyme-treated soybean meal are well tolerated by young pigs and may replace fishmeal or animal proteins in weanling pig diets.

Introduction

In 2012, the U.S. produced 31% (82.0 million tons) of the world's soybeans, making it the second largest soybean producer after Brazil (Soyatech, 2014). However, the U.S. is predicted to produce 88.6 million tons of soybeans during the 2013-2014 harvest season, which would once again make the U.S. the world's top soybean producer. The majority of soybeans are dehulled, defatted, and crushed to produce soybean meal (**SBM**) that is then fed to livestock. Due to its favorable nutrient and digestible amino acid (**AA**) composition, SBM is the primary protein source fed to livestock (Shelton et al., 2001), with pigs consuming approximately 26% of total SBM produced (Stein et al., 2008; ASA, 2013).

Raw soybeans contain antinutritional factors, such as trypsin inhibitors, oligosaccharides, antigenic proteins, and lectins. To remove trypsin inhibitors and lectins, SBM is toasted. Trypsin inhibitors are known for binding to trypsin, chymotrypsin, and other enzymes, which ultimately decrease AA digestibility and growth performance in pigs (Yen et al., 1977; Goebel and Stein, 2011). However, because of the other antinutritional factors in SBM, weanling pigs have a difficult time digesting SBM, and as a consequence, they will experience a temporary decrease in nutrient digestibility and reduced growth performance if fed diets containing high levels of SBM (Li et al., 1990, 1991; Friesen et al., 1993; Qin et al., 1996). The temporary decrease in nutrient digestibility is the result of transient hypersensitivity to the soy protein, which causes villus atrophy in the small intestine of weanling pigs (Li et al., 1990). Therefore, SBM inclusion in weanling pig diets is usually restricted to less than 20%.

Fermentation or enzyme treatment of SBM removes the antigenic proteins (Sissons, 1982), and these products can be fed as replacements for animal proteins such as fish meal without negatively affecting growth (Jones et al., 2010; Kim et al., 2010). As a consequence, in the last decade, interest has increased in feeding fermented soybean meal (**FSBM**) or enzyme-treated soybean meal (**ESBM**) to potentially mitigate the effects of transient hypersensitivity by deactivating these antigenic proteins and removing oligosaccharides.

Energy and Nutrient Composition

Energy

Soybean meal is primarily classified as a protein source, but it also contributes energy to the diet. Soybean meals from different growing regions of the U.S. contain similar concentrations of nutrients and antinutritional factors (Table 1; Sotak and Stein, 2014). However, SBM from the western growing region of the United States has decreased energy and crude protein (**CP**) concentrations compared with the northern and eastern growing regions of the U.S. The energy values for SBM observed in research conducted at the Uni-

versity of Illinois between 2010 and 2013 (Goebel and Stein, 2011b; Rodriguez et al., 2013; Rojas and Stein, 2013a; Sulabo et al., 2013; Yoon and Stein, 2013; Baker et al., 2014; Sotak and Stein, 2014) are greater than energy values reported by NRC (1998; 2012). It is, therefore, possible that the NRC (1998; 2012) underestimates the energy concentrations of SBM.

Fermented SBM and ESBM have greater concentrations of CP, acid detergent fiber (**ADF**), and neutral detergent fiber (**NDF**) because fermentation removes sucrose and oligosaccharides from the SBM (Cervantes-Pahm and Stein, 2010; Rojas and Stein, 2013b). Energy values for FSBM and ESBM are greater compared with energy values of SBM (Table 2). The increase in energy for FSBM and ESBM is due to increased concentrations of CP and decreased concentrations of antinutritional factors and antigenic proteins.

Carbohydrates

Soybeans are a major contributor of carbohydrates to the diet and contain 30 to 35% carbohydrates. These carbohydrates are classified as either structural (e.g., cellulose, hemicellulose, or lignin) or non-structural (e.g., sugars, oligosaccharides, or starch; Table 3; Grieshop et al., 2003). All non-structural carbohydrates are soluble and easily fermented by the pig, but only some structural carbohydrates are soluble and fermentable. The remaining structural carbohydrates are not easily fermented by the pig, which decreases the energy the pig can obtain from the ingredient.

On average, SBM contains 5 to 7% oligosaccharides (Karr-Lilienthal et al., 2005). When 2% stachyose was added to weanling pig diets, a greater decrease in growth performance was observed compared with weanling pigs fed diets containing 20% SBM (Liying et al., 2003). Pigs fed 1% stachyose had similar growth performance and decreased incidence of diarrhea compared with pigs fed SBM (Liying et al., 2003); therefore, other antinutritional factors, such as glycinin, may be a factor in the transient hypersensitivity observed in weanling pigs (Li et al., 1991). Pre-exposure to SBM prior to weaning did not affect growth performance in weanling pigs (Friesen et al., 1993). However, FSBM and ESBM contain almost no oligosaccharides due to hydrolysis of oligosaccharides during the fermentation process (Cervantes-Pahm and Stein, 2010), which may make them more digestible to weanling pigs and mitigate transient hypersensitivity. Jones et al. (2010) observed similar daily gains and daily feed intakes, but improved gain:feed ratios, in pigs fed increasing levels of FSBM.

Dietary fiber components include ADF, NDF, and lignin, and are not easily fermentable by the pig, which causes a decrease in dry matter digestibility. Ingredients containing higher fiber concentrations have a decreased dry matter digestibility because dietary fiber increases the rate of passage in the intestine, which decreases time for absorption. However, whereas SBM, FSBM, and ESBM have similar concentrations of dietary fiber, these concentrations are low compared with other protein sources, such as canola meal, distillers dried grains with solubles (**DDGS**), and sunflower meal (Table 4).

Phosphorus and Calcium

Phosphorus aides in skeletal support, and is also important in lipid metabolism and transport, and cell membrane structure (Pond et al., 2005). Total phosphorus (**P**) is the sum of phytate bound P, inorganic P, and other P found in SBM (Table 5). Phytate-bound P is unavailable to pigs because they lack the phytase enzyme (Paulsen, 2008). When microbial phytase is added to the diet, apparent total tract digestibility (**ATTD**) of P and standardized total tract digestibility (**STTD**) of P increase (Almeida and Stein, 2010), which ultimately decreases fecal P by 35% (Simons et al., 1990). Fermented SBM has increased ATTD and STTD of P compared with SBM, but FSBM and SBM had similar ATTD and STTD of P when microbial phytase was added to the diet (Rojas and Stein, 2012). During the fermentation process, the phytate bonds may have been hydrolyzed, which increased the concentration of free P available to the pig (Ilyas et al., 1995). Enzyme-treated SBM had similar ATTD and STTD of P compared with SBM; however, an increase was observed when the enzyme mixture contained phytase. When microbial phytase was added to diets, pigs fed ESBM had similar ATTD and STTD of P compared with pigs fed SBM (Goebel and Stein, 2011b).

Not only does phytate bind P, but it also binds calcium (**Ca**), which ultimately decreases its absorption (Paulsen, 2008). The ATTD and STTD of Ca increased for FSBM, ESBM, and SBM when microbial phytase was added to the diet (Goebel and Stein, 2011b; Rojas and Stein, 2012).

Protein and Amino Acids

Soybean meal is the premiere source of protein for pigs because the **AA** profile is complementary to several cereal grains, such as corn, sorghum, barley, and wheat. Soybean protein is rich in lysine, threonine, and tryptophan, but deficient in sulfur AA. Cereal grains tend to be deficient in lysine, threonine, and tryptophan, but rich in sulfur AA. Proteins in SBM are highly digestible, and have a greater standardized ileal digestibility (**SID**) compared with canola meal and corn DDGS

(Gonzalez-Vega et al., 2012; NRC, 2012). Soybean meal not only has increased SID of CP compared with canola meal and corn DDGS, but also contains more AAA and less dietary fiber. Therefore, SBM supplies more energy to pigs compared with canola meal.

The concentration of CP in SBM is greater than in soybeans because of the removal of fat and the hulls. With the removal of oligosaccharides and antigenic proteins during fermentation, FSBM and ESBM have greater concentrations of CP compared with SBM (Table 2; Cervantes-Pahm and Stein, 2010). Fermented SBM and ESBM have similar SID of AA compared with SBM, but adding fat to diets increases SID of AA because it decreases the rate of intestinal passage, allowing for increased absorption (Table 6; Cervantes-Pahm and Stein, 2008).

Another advantage of using SBM as the protein source instead of other protein sources (e.g., canola meal, corn DDGS, or sunflower meal) is decreased variability among batches of product (Table 7). Variability among batches is challenging when formulating diets due to a decrease in confidence in digestibility values; therefore, swine nutritionists have more confidence in digestibility values in SBM compared with other protein sources.

Fat

Soybean oil contains approximately 79% unsaturated fatty acids and 14.5% saturated fatty acids (Table 8). The major fatty acid in soybean oil is linoleic acid (C18:2; 50% of total). Soybean oil also contains approximately 6% linolenic acid (C18:3), which may have anti-inflammatory properties in diets fed to pigs (NRC, 2012). Because soybean oil contains a large portion of unsaturated fatty acids, issues with processing pork bellies and loins and decreased shelf life can occur if large quantities of soybean oil are used during the finishing phase.

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Table 1. Energy and nutrient composition of soybean meal (SBM) from different regions of the U.S.

	Zone[1]					
Item	**1**	**2**	**3**	**4**	**Average[2]**	***P*-value[3]**
GE, kcal/kg	4,165	4,209	4,162	4,198	4,184	0.08
DE, kcal/kg DM	3,882[a]	3,875[a]	3,835[b]	3,858[ab]	3,863	0.02
ME, kcal/kg DM	3,732[ab]	3,736[a]	3,694[b]	3,718[ab]	3,720	0.02
DM, %	88.60	88.71	88.30	89.03	88.66	0.18
CP, %	46.64[ab]	48.44[a]	46.50[b]	48.06[a]	47.41	0.03
AEE, %[4]	1.11[ab]	0.86[b]	1.37[a]	0.69[b]	1.01	0.04
ADF, %	4.81	5.20	4.89	4.76	4.91	0.34
NDF, %	7.78	7.53	8.21	8.94	8.11	0.13
Lignin, %	0.60	0.59	0.58	0.63	0.58	0.13
Ca, %	0.34	0.30	0.47	0.42	0.38	0.06
P, %	0.63	0.65	0.67	0.64	0.65	0.07

[a-d] Means within a row lacking a common superscript letter are different ($P < 0.05$).
1 Zone 1 = northern growing area (MI, MN, and SD); Zone 2 = eastern growing area (GA, IN, and OH); Zone 3 = western growing area (IA, MO, and NE); Zone 4 = IL.
2 Average is for the 22 sources of SBM.
3 *P*-values compare SBM within the 4 zones and are considered significant at $P \leq 0.05$.
4 AEE = acid hydrolyzed ether extract.

Table 2. Energy and nutrient composition of soybean meal (SBM), fermented soybean meal (FSBM), and enzyme-treated soybean meal (ESBM; as fed basis).[1]

Item	**SBM**	**FSBM**	**ESBM**
GE, kcal/kg	4,256	4,533	4,451
DE, kcal/kg	3,619	3,975	3,914
ME, kcal/kg	3,294	3,607	3,536
DM, %	89.98	92.88	92.70
CP, %	47.73	54.07	55.62
EE, %	1.52	2.30	1.82
Ca, %	0.33	0.29	0.31
P, %	0.49	0.80	0.75

1 Values obtained from NRC (2012); Goebel and Stein, 2011; Rojas and Stein, 2013b.

Table 3. Carbohydrates in soybean meal (SBM), fermented soybean meal (FSBM), and enzyme-treated soybean meal (ESBM).[1]

Item, %	**SBM**	**FSBM**	**ESBM**
Sucrose	4.30	ND[2]	0.20
Stachyose	7.33	0.06	0.24
Raffinose	3.78	ND	0.35
Verbascose	ND	-	-
ADF	5.28	4.53	5.37
NDF	8.21	8.82	11.43
Lignin	1.10	-	-
Starch	1.89	0.90	-

1 Values obtained from Goebel and Stein, 2011b; NRC, 2012; Rojas and Stein, 2013.
2 ND = Not detected.

Table 4. Dietary fiber content of protein sources, %.[1]

Item, %	Soybean meal	Corn DDGS	Canola meal	Sunflower meal
ADF	5.28	12.02	15.42	23.00
NDF	8.21	30.46	22.64	30.24
Lignin	1.10	5.05	3.36	8.6
Crude fiber	3.89	8.92	10.50	18.44

[1] Values obtained from NRC, 2012.

Table 5. Concentrations and apparent total tract digestibility (ATTD) and standardized total tract digestibility (STTD) of phosphorus (P) and calcium (Ca) in soybean meal (SBM), fermented soybean meal (FSBM), and enzyme-treated soybean meal (ESBM).[1]

Item, %	SBM	FSBM	ESBM
Total P	0.71	0.80	0.75
ATTD of P	39.00	60.90	60.00
STTD of P	48.00	65.50	66.00
Phytate-bound P	0.38	0.40	-
Phytate-bound of total P	53.5	50.00	-
Non-phytate P	0.33	0.40	-
Non-phytate bound P of total P	46.50	50.00	-
Total Ca	0.33	0.29	0.31

[1] Values obtained from Goebel and Stein, 2011; NRC, 2012; Rojas and Stein, 2012.

Table 6. Standardized ileal digestibility (SID, %) of crude protein (CP) and amino acids (AA) in soybean meal (SBM), fermented soybean meal (FSBM), and enzyme-treated soybean meal (ESBM).[1]

Item, %	SBM	FSBM	ESBM
CP	87	79	88
Indispensable AA			
Arginine	94	90	96
Histidine	90	81	90
Isoleucine	89	82	89
Leucine	88	82	89
Lysine	89	75	86
Methionine	90	88	91
Phenylalanine	88	80	86
Threonine	85	73	83
Tryptophan	91	78	83
Valine	87	80	89
Dispensable AA			
Alanine	85	79	86
Aspartic acid	87	78	86
Cysteine	84	64	73
Glutamic acid	89	78	88
Glycine	84	75	89
Serine	89	80	87
Tyrosine	88	88	92

[1] Values obtained from NRC, 2012.

Table 7. Variability in standardized ileal digestibility (SID) of amino acids (AA) expressed as standard deviation (SD) in soybean meal (SBM), corn distiller's dried grains with solubles (DDGS), canola meal, and sunflower meal.[1]

	SBM		DDGS		Canola meal		Sunflower meal	
AA	**SID**	**SD**	**SID**	**SD**	**SID**	**SD**	**SID**	**SD**
Arginine	94	3.12	81	5.25	85	5.56	93	3.35
Histidine	90	4.15	78	4.75	78	10.24	85	6.28
Isoleucine	89	3.79	76	4.87	76	8.34	80	6.15
Leucine	88	3.45	84	4.00	78	6.44	80	5.27
Lysine	89	3.44	61	8.75	74	9.65	78	5.13
Methionine	90	4.70	82	4.13	85	4.06	89	-
Phenylalanine	88	3.65	81	3.96	77	8.42	81	7.11
Threonine	85	4.47	71	5.73	70	9.64	77	8.54
Trypeophan	91	3.32	71	8.16	71	-	80	-
Valine	87	4.16	75	4.95	74	9.78	79	8.06

[1] Values obtained from NRC, 2012.

Table 8. Fatty acid profile (% of ether extract) and iodine value of full-fat soybeans.[1]

Fatty acid	Abbreviation	%
Myristoleic acid	C-14:0	0.28
Palmitic acid	C-16:0	10.62
Palmitoleic acid	C-16:1	0.28
Stearic acid	C-18:0	3.57
Oleic acid	C-18:1	21.81
Linoleic acid	C-18:2	49.79
Linolenic acid	C-18:3	6.67
Saturated fatty acids	-	14.46
Monounsaturated fatty acids	-	22.09
Polyunsaturated fatty acids	-	56.46
Iodine value	-	128.24

[1] Values obtained from NRC, 2012.

Soybean Meal and the Immune Response to PRRS Virus

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Summary

An experiment was conducted to determine the effects of dietary soybean meal (SBM) concentration on the growth performance and immune response of pigs infected with porcine reproductive and respiratory syndrome virus (PRRSV). Four experimental treatments included a 2 × 2 factorial arrangement of 2 dietary SBM concentrations, 17.5% (LSBM) and 29% (HSBM), and 2 levels of PRRSV infection, uninfected (sham) and PRRSV-infected. Weanling pigs (32 barrows and 32 gilts, 21 days of age, 7.14 ± 0.54 kg) were individually housed in disease containment chambers. Pigs were provided a common diet for 1 week before being allotted to 4 treatment groups with 16 replicate pigs per group. Pigs were fed experimental diets for 1 week before receiving either a sham inoculation (sterile PBS) or a 1 × 10^5 50% tissue culture infective dose of PRRSV at 35 days of age (0 d post-inoculation, DPI). Growth performance was recorded weekly, and rectal temperatures were measured daily beginning on 0 DPI. Blood was collected on 0, 3, 7 and 14 DPI for determination of differential complete blood cell counts, serum PRRSV load, and haptoglobin and cytokine concentrations. Infection with PRRSV increased (P < 0.01) rectal temperatures of pigs from 0 to 14 DPI, with no influence of dietary SBM concentration (P > 0.05). In the PRRSV-infected group, pigs fed HSBM tended to have improved daily gain (P = 0.06) and gain:feed (P = 0.09) over pigs fed LSBM. No effects of dietary SBM concentration on leukocyte measurements were observed within the PRRSV-infected group at any time point. Serum PRRSV load of PRRSV-infected pigs tended to be lower (P = 0.06) in pigs fed HSBM than pigs fed LSBM at 14 DPI, but no differences were observed at 3 or 7 DPI. Serum haptoglobin and tumor necrosis factor-α concentrations of PRRSV-infected pigs were greater (P > 0.05) at 3 and 14 DPI, respectively, in pigs fed LSBM than pigs fed HSBM. Overall, it appears that the immunological stress elicited by PRRSV infection was decreased in pigs fed HSBM compared with pigs fed LSBM, which may have contributed to the tendency for improved growth rate and feed efficiency of the HSBM-fed pigs during the 14 day infection period.

Introduction

Porcine reproductive and respiratory syndrome (**PRRS**), caused by the PRRS virus (**PRRSV**), is the most prevalent disease of swine globally (Lunney et al., 2010). Infection of nursery pigs with PRRSV leads to a complex immune response that results in fever, lethargy, respiratory stress, reduced feed intake, and ultimately decreased growth performance (Rossow, 1998). In 2005, Neumann et al. (2005) assessed the financial impact of PRRS and reported annual losses of $560 million for U.S. swine producers due to PRRS. In an updated report published in 2012, these authors estimated the annual impact of PRRS on the U.S. swine industry to be $664 million (Holtkamp et al., 2012). Therefore, despite much effort from researchers and swine producers, PRRS continues to pose a substantial financial burden for the U.S. swine industry.

Soybean meal (**SBM**) is the primary dietary source of crude protein (**CP**) and amino acids (**AA**) for swine in the U.S. Soybeans and soybean feedstuffs also contain the isoflavones genistein, daidzein, and glycitein, and these compounds are considered to have a range of biological activities, including antiviral effects, when included in the diet (Andres et al., 2009). Greiner et al. (2001a, b) evaluated graded concentrations of purified genistein and daidzein in diets of pigs infected with PRRSV. These authors determined that while daidzein had minimal impact on immune function or growth of PRRSV-infected pigs, genistein at 200 to 400 mg/kg positively modulated the immune response to PRRSV and improved body weight gain. Thus, it was of interest to evaluate the effects of SBM inclusion, which would concurrently increase both dietary CP and isoflavone concentrations, on the response of pigs infected with PRRSV. The objective of the current study was to evaluate 2 levels of dietary SBM on the immune response, viremia, and growth performance of weanling pigs receiving an acute PRRSV infection.

Experimental Procedures

Animals, Experimental Design, and Diets

Sixty-four weanling pigs (32 barrows, 32 gilts; 21 days of age; 7.14 ± 0.54 kg BW) were obtained from the University of Illinois Swine Research Center and individually-housed in a disease containment facility at the University of Illinois for 4 weeks (-14 to 14 days post-inoculation, **DPI**). Upon arrival, 3 consecutive daily intramuscular injections of lincomycin (11 mg/kg of BW; Zoetis, Florham Park, NJ) were administered as a precautionary measure against bacterial infections. The disease containment facility consisted of 2 hallways with access to 8 independently HEPA-filtered chambers in each hallway. Each chamber was divided into 4 individual pens (0.84 m^2 per pig) with coated expanded metal flooring. Lights were provided on a 12 hour cycle, and temperature was maintained at approximately 26°C. Pigs had *ad libitum* access to feed and water throughout the trial. A common diet that met or exceeded NRC (2012) nutrient requirements for weanling pigs was provided for 1 week (-14 to -7 DPI), and at -7 DPI, pigs were weighed and allotted to 4 uniform blocks based on body weight, sex, and litter of origin.

Four experimental treatments comprised a 2 × 2 factorial arrangement of 2 dietary SBM concentrations and 2 PRRSV infection states (uninfected sham or PRRSV-infected). Each of 16 replicate pigs received 1 of the 4 experimental treatments. The low SBM (**LSBM**) diet contained 17.5% SBM, while the high SBM (**HSBM**) diet contained 29.0% SBM (Table 1). The experimental diets were formulated to be isocaloric and contain equal digestible concentrations of Lys, Met, Trp, Thr, and Val. Isoflavone and saponin concentrations of the experimental diets were determined using HPLC according to the procedures of Berhow et al. (2006) at the USDA-ARS National Center for Agricultural Utilization Research (Peoria, IL). Pigs were provided a 1 week adaptation period (-7 to 0 DPI) to the experimental diets before being intranasally inoculated with either 2 mL of Dulbecco's PBS (sham control) or a 1×10^5 50% tissue culture infective dose of PRRSV (P-129 isolate, Purdue University, West Lafayette, IN) diluted in 2 mL of Dulbecco's PBS. Chambers with uninfected and PRRSV-infected pigs were located in separate hallways to avoid cross-contamination. Pigs within blocks were allotted such that each experimental diet was represented twice (1 barrow and 1 gilt fed each diet) within each chamber.

Growth Performance, Rectal Temperatures, and Blood Collection and Analysis

Individual pig and feeder weights were recorded weekly throughout the trial to allow for calculation of average daily gain (**ADG**), average daily feed intake (**ADFI**), and feed efficiency (gain:feed; **G:F**). Growth performance data are reported in reference to the inoculation schedule (-14 to 14 DPI). Rectal temperatures were measured daily for 14 days beginning immediately before inoculation (0 DPI) using a digital thermometer. Blood was collected from each pig via the jugular vein into evacuated tubes (BD, Franklin Lakes, NJ) at 0, 3, 7, and 14 DPI. Blood was processed to obtain serum samples using standardized procedures and samples were stored at -20°C pending analyses.

Serum PRRSV load was measured at 0, 3, 7, and 14 DPI by extracting PRRSV RNA and analyzing with real-time reverse transcription PCR (University of Illinois Veterinary Diagnostic Laboratory, Urbana, IL). Viral load was expressed as cycle threshold (**Ct**) values, where a higher Ct value represents a lower amount of PRRSV RNA. Serum concentrations of interferon-γ, tumor necrosis factor alpha (**TNF-α**), interleukin-10, interleukin-1 beta (**IL-1β**), and haptoglobin were measured in duplicate using sandwich ELISA kits according to procedures specified by the manufacturers (cytokines, R&D Systems, Minneapolis, MN; haptoglobin, GenWay Biotech, Inc., San Diego, CA). A microplate reader (BioTek, Winooski, VT) was used to determine the optical density of samples in each well, and analyte concentrations were calculated using standard curves for each plate. Serum concentrations of interferon-γ and interleukin-10 were below minimum detectable levels for all time periods, so data for these cytokines are not presented.

Statistical Analyses

A repeated measures analysis of variance was conducted where each individual pig was considered an experimental unit (16 replicate pigs for each of the 4 experimental treatments). Data were subjected to a 3-way ANOVA using the Proc Mixed procedure of SAS 9.3 (SAS Institute, Inc., Cary, NC) with the following statistical model:

$$Y_{ijkl} = \mu + \alpha_i + \beta_j + \alpha\beta_{ij} + \gamma_k + \alpha\gamma_{ik} + \beta\gamma_{jk} + \alpha\beta\gamma_{ijk} + \varepsilon_{ijkl}$$

where α_i = the fixed effect of diet, β_j = the fixed effect of infection status, $\alpha\beta_{ij}$ = the interaction between diet and infection status, γ_k = the fixed effect of DPI, $\alpha\gamma_{ik}$ = the interaction between diet and DPI, $\beta\gamma_{jk}$ = the interaction between infection status and DPI, $\alpha\beta\gamma_{ijk}$ = the 3-way interaction between diet, infection status, and DPI, and ε_{ijkl} = experimental error. Orthogonal contrasts were utilized to evaluate effects of dietary treatment on pigs within the same infection treatment. Statistical significance was considered at $P \leq 0.05$.

Results

Growth Performance

Average daily gain and G:F of pigs fed HSBM from -7 to 0 DPI indicated that the increased dietary SBM concentration tended to improve ($P = 0.07$) growth performance compared with pigs fed LSBM during the week before inoculation (Table 2). During the first week post-inoculation, PRRSV-infection reduced ($P < 0.01$) ADFI, ADG, and G:F, and interactive effects of SBM concentration and PRRSV-infection were observed during this period. However, orthogonal contrasts indicated no differences ($P > 0.05$) in growth performance between pigs fed LSBM or HSBM within the uninfected or PRRSV-infected groups.

Overall, PRRSV-infection reduced ($P < 0.01$) ADFI, ADG, and G:F during the 2 week infection period (0 to 14 DPI). No main effects of SBM inclusion or interactions between SBM inclusion and PRRSV-infection were observed for ADFI or G:F from 0 to 14 DPI, but an interaction ($P < 0.05$) was observed for ADG. This interaction was due to the tendency ($P = 0.06$) of greater ADG in pigs fed HSBM over those fed LSBM in the PRRSV-infected group, with no effects of SBM inclusion in the uninfected group. There was also a tendency for greater G:F for pigs fed HSBM over those fed LSBM within the PRRSV-infected group, with no difference in G:F of pigs due to SBM level in the uninfected group. In the PRRSV-infected group, pigs fed HSBM had higher ($P < 0.01$) final body weights at 14 DPI compared with pigs fed LSBM, whereas there was no difference ($P > 0.05$) between final body weights of LSBM and HSBM-fed pigs in the uninfected group.

Rectal Temperatures and Serum Measurements

Acute infection with PRRSV increased ($P < 0.01$) rectal temperatures of pigs during the 14 d infection period, with no influence ($P > 0.05$) of dietary SBM inclusion (Figure 1). Viral gene expression indicated that all pigs were free of PRRSV on 0 DPI, all infected pigs were PRRSV-positive at 3, 7, and 14 DPI, and that all sham-inoculated pigs remained PRRSV-free throughout the trial. No effects ($P > 0.05$) of dietary SBM concentration were observed for serum viral load at 3 or 7 DPI, but Ct values indicated a reduced ($P < 0.05$) serum PRRSV load in HSBM-fed pigs compared with LSBM-fed pigs at 14 DPI (Figure 2).

At 3 DPI, an interaction ($P < 0.01$) between dietary SBM concentration and PRRSV-infection was observed for serum haptoglobin concentration, with no differences ($P > 0.10$) due to diet in the uninfected group, but greater ($P = 0.03$) serum haptoglobin concentration for pigs fed LSBM over those fed HSBM in the PRRSV-infected group. An interaction ($P < 0.01$) was also observed for both TNFα and IL-1β at 3 DPI, indicating that the PRRSV-induced increase in these cytokines was not equal between pigs fed LSBM and HSBM. At 7 and 14 DPI, interactive effects ($P < 0.01$) were detected for haptoglobin, TNFα, and IL-1β, but orthogonal contrasts between pigs fed LSBM and HSBM within either infection group were not generally different ($P > 0.10$) for any of these analytes. There was one exception, however, as TNF-α concentrations of PRRSV-infected pigs fed HSBM were lower ($P < 0.01$) than PRRSV-infected pigs fed LSBM at 14 DPI.

Discussion

Acute infection of weanling pigs with PRRSV leads to a complex immune response that results in fever, lethargy, respiratory stress, reduced feed intake, and ultimately decreased growth performance (Rossow, 1998). Previous research concerning the interaction of nutrition and PRRSV infection has been limited to specific nutrients and specialty additives with mixed results, but the effects of major feed ingredients on PRRSV-infected pigs are largely unknown. Soybean meal was chosen for investigation in this experiment as a potentially beneficial ingredient due to the naturally occurring isoflavones found within SBM that have been demonstrated to exert anti-viral activity both *in vitro* and *in vivo* (Andres et al., 2007; Greiner et al., 2001a, b). Furthermore, the continuous availability of SBM for use in swine diets makes feasible the use of HSBM diets as a rapid strategy for swine producers in response to a PRRS outbreak. In the current experiment, pigs consuming 29% dietary SBM generally maintained better growth performance compared with pigs fed 17.5% dietary SBM both before and during a 14 d acute PRRSV infection. Moreover, pigs fed HSBM had reduced levels of inflammatory biomarkers compared with those fed LSBM at 3 and 14 DPI, as well as a reduced serum viral load at 14 DPI. Therefore, while the mechanism of action remains unclear, these findings suggest that feeding a HSBM diet may help to minimize immune stress and maintain growth performance of weanling pigs during an acute PRRSV infection.

During the first week of infection, pigs in the PRRSV-infected group had increased rectal temperatures, decreased appetites, and were PRRSV positive as indicated by serum viral loads. Additionally, all pigs in the uninfected group tested negative for PRRSV and were free of clinical symptoms associated with PRRS throughout the study, further indicating a successful infection model. The impact of PRRSV infection on the growth performance of pigs in the current study was slightly less severe when compared with previous studies at our

research facility using similar infection models. In the current experiment, PRRSV infection reduced overall ADG and G:F 42% and 18%, respectively, whereas Che et al. (2011) and Liu et al. (2013) reported reductions of 59% and 47% for ADG and 29% and 33% for G:F, respectively, due to PRRSV infection.

The greatest serum PRRSV load observed in the current study occurred at 7 DPI, which is in agreement with previous reports of peak serum PRRSV concentration within the first 10 days following infection (Che et al., 2011; Greiner et al., 2000; Liu et al., 2013). There was no influence of dietary SBM on serum viral load during the initial or peak phase of infection, but at 14 DPI, pigs fed the HSBM diet had a lower viral load than those fed the LSBM diet, suggesting that these pigs may have had an improved ability to eliminate the virus during the initial stages of recovery. Serum PRRSV concentration is negatively correlated with feed intake (Greiner et al., 2000), and thus, the reduced serum PRRSV load at 14 DPI may have contributed to the trend in greater ADFI and improved ADG for pigs fed the HSBM diet during the 7 to 14 DPI period.

Infection of pigs with PRRSV in the current study led to elevated serum concentrations of IL-1β and TNF-α beginning at 3 DPI, with the greatest concentrations observed at 14 DPI. Both of these inflammatory cytokines function as endogenous pyrogens and induce anorexia, ultimately reducing growth performance of animals during immune stress. Considering the 4.5-fold increase in TNF-α due to PRRSV-infection at 14 DPI, it was interesting to note that consumption of the HSBM diet was able to reduce expression of this cytokine by 20% in PRRSV-infected pigs at this time-point. Moreover, there was a marked PRRSV-induced increase in the serum concentration of the acute-phase protein, haptoglobin, at 3 DPI for pigs fed LSBM compared with those fed HSBM. Serum haptoglobin concentration has been shown to increase in pigs during PRRSV infection, but the timing, magnitude, and duration of its increased synthesis in response to PRRSV infection is variable (Che et al., 2011; Gnanandarajah et al., 2008; Liu et al., 2013). Although serum IL-1β and TNF-α concentrations of pigs within the PRRSV group were not influenced by diet at 3 DPI, the lower serum haptoglobin concentrations of pigs fed the HSBM diet may indicate reduced secretion of pro-inflammatory cytokines during the first few days following infection. However, the effect of dietary SBM level on serum haptoglobin concentration of pigs within the PRRSV group was diminished by 7 DPI.

Considering the anti-inflammatory effects observed as a result of increased SBM concentration, one is left wondering about the mechanism of action, and we have focused our attention on both soy-derived bioactive compounds and greater CP delivered by the HSBM diet. Soybeans and soybean-derived feedstuffs are the richest sources of the isoflavones genistein, daidzein, and glycitein (Wang and Murphy, 1994), which are reported to exert both anti-inflammatory and anti-viral activity through various mechanisms. Therefore, it is possible that the immunomodulatory and beneficial effects of the HSBM diet on the growth performance of PRRSV-infected pigs in the current study may be partly explained by the concomitant increase in isoflavone concentration of the HSBM diet. A plethora of *in vitro* studies indicate that genistein may potentially inhibit virus-cell binding and entry, virus replication, viral protein translation, and viral envelope formation of a multitude of viruses (Andres et al., 2009). Greiner et al. (2001a, b) evaluated the effects of adding supplemental, purified dietary genistein or daidzein up to 800 mg/kg to a diet devoid of isoflavones on the immune response and growth performance of pigs infected with PRRSV. A quadratic response in ADFI was observed for pigs fed increasing concentrations of dietary genistein, with the greatest ADFI and ADG observed for pigs fed 200 mg/kg genistein. Furthermore, a linear decrease in serum PRRSV concentration and a quadratic decrease in IFN-γ were observed with increasing dietary genistein concentration, while spleen size increased linearly. In a separate experiment using the same model, daidzein had minimal influence on these same measurements with the exception of a linear increase in spleen size.

In the current experiment, dietary genistein concentration of the LSBM diet (369 mg/kg) was within the range (200 to 400 mg/kg) suggested by Greiner et al. (2001b) to have potential immunomodulatory and growth-enhancing effects in PRSSV-infected pigs, while genistein concentration of the HSBM diet (638 mg/kg) exceeded this range. Bioavailability of isoflavones is certainly influenced by the feed matrix (Cassidy et al., 2006), so it is entirely possible that the isoflavones contributed by SBM in the current study were less bioavailable than those provided in a supplemental, purified form by Greiner et al. (2001a, b).

In addition to a greater concentration of isoflavones, the HSBM diet fed to pigs in the current experiment certainly contained higher levels of other nutrients compared with the LSBM diet, most notably CP. It is has been suggested that feeding a low CP diet, particularly when no in-feed antibiotics are used, may be the single most effective strategy to minimize post-weaning diarrhea and improve the growth performance of nursery pigs (Stein and Kil, 2006). Accordingly, complex diets are often formulated to contain minimal SBM and CP concentrations to minimize gastrointestinal stress during the first few weeks post-weaning, when pigs are

especially susceptible to enteric pathogens such as enterotoxigenic *Escherichia coli*. To maintain biosecurity and minimize the risk of confounding secondary infections, the disease-containment facility utilized in our study was thoroughly sanitized each day. Therefore, environmental conditions were much more sanitary than would be found in conventional production facilities, possibly diminishing the adverse risks of feeding a high CP diet.

Experimental diets in the current study were balanced to contain similar concentrations of standardized ileal digestible lysine, methionine, tryptophan, and threonine. Beyond these AA, the higher SBM and CP concentrations of the HSBM diet resulted in an average increase of 25% for both indispensable and dispensable AA. The greatest increase was for arginine, followed by isoleucine and phenylalanine, which were 32, 26, and 26% higher, respectively, in the HSBM diet compared with the LSBM diet. Activation of the immune system may alter AA requirements (Klasing, 1988), and the surfeit AA supply of the HSBM diet may have supported an increased AA demand for production of immune-specific molecules during the PRRSV infection. Furthermore, inflammatory cytokine secretion following immune activation induces a metabolic shift in which body protein is catabolized to liberate AA that are subsequently deaminated and oxidized via gluconeogenesis (Klasing, 1988). Excess AA in the HSBM diet may have served as gluconeogenic substrates to meet a greater energy demand in the PRRSV-infected pigs. However, the current study was unable to definitively discern whether the beneficial effects of feeding increased SBM to PRRSV-infected weanling pigs were due to isoflavones or AA, so further studies are warranted to define an immunomodulatory mechanism.

In conclusion, it appears that the immunological stress elicited by PRRSV infection was decreased in weanling pigs fed HSBM compared with pigs fed LSBM, which may have contributed to the tendency for improved ADG and feed efficiency of the HSBM-fed pigs during the 14 d infection.

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Table 1. Composition of experimental diets fed to weanling pigs during the experiment (as-fed basis).[1]

Item	LSBM	HSBM
Ingredient, %		
Corn	46.13	35.55
Soybean meal	17.50	29.00
Dried whey	14.95	14.95
DDGS	10.00	10.00
Poultry by-product meal	7.00	7.00
Choice white grease	1.50	1.50
Ground limestone	0.68	0.60
Monocalcium phosphate	0.27	0.20
Sodium chloride	0.40	0.40
Vitamin and mineral premix	0.30	0.30
Choline chloride	0.07	0.07
L-lysine HCl	0.60	0.24
DL-methionine	0.27	0.16
L-Tryptophan	0.08	0.03
L-Threonine	0.15	- -
L-Valine	0.10	- -
Calculated composition		
ME, kcal/kg	3,402	3,398
SID amino acids, %		
Lysine	1.38	1.38
Methionine + cysteine	0.83	0.83
Tryptophan	0.26	0.26
Threonine	0.86	0.87
Calcium, %	0.80	0.80
Available phosphorus, %	0.40	0.40
Analyzed composition		
Crude protein (N × 6.25), %	22.75	26.65
Total amino acids, %		
Lysine	1.58	1.66
Methionine + cysteine	0.88	0.95
Tryptophan	0.35	0.35
Threonine	0.95	1.03
Isoflavones, mg/kg		
Geinistein	369	638
Daidzein	257	513
Glycitein	76	96
Total isoflavones	700	1,246

[1] All pigs received a common nursery diet for 7 days immediately following weaning at 3 weeks of age. Pigs were then provided either the low soybean meal (LSBM) or high soybean meal (HSBM) diet for the remainder of the trial.

Table 2. Effects of dietary soybean meal concentration and porcine reproductive and respiratory virus (PRRSV) infection on growth performance of weanlings pigs.[1]

						P-value				
	Uninfected		PRRSV-infected			Main effects		Diet ×	LSBM vs. HSBM[2]	
Item	LSBM	HSBM	LSBM	HSBM	SEM	Diet	PRRSV	PRRSV	Uninfected	PRRSV-infected
BW, kg										
-7 DPI	7.87	7.76	7.76	7.89	0.23	0.94	0.97	0.58	0.74	0.65
14 DPI	17.59	17.01	13.39	14.73	0.35	0.27	<0.01	<0.01	0.23	<0.01
-7 to 0 DPI[3]										
ADFI, g/d	479	391	425	478	31.7	0.57	0.60	0.14	0.05	0.23
ADG, g/d	172	184	171	253	26.5	0.07	0.19	0.09	0.75	0.03
G:F, g/kg	412	455	403	515	43.8	0.07	0.54	0.24	0.47	0.06
0 to 14 DPI										
ADFI, g/d	885	842	592	618	27.6	0.76	<0.01	0.21	0.27	0.50
ADG, g/d	608	576	314	374	21.8	0.52	<0.01	0.04	0.30	0.06
G:F, g/kg	693	703	535	605	28.4	0.16	<0.01	0.29	0.81	0.09

[1] Values represent 15-16 pigs per treatment combination of diet and PRRSV inoculation. Abbreviations: LSBM = low soybean meal, HSBM = high soybean meal, DPI = days post-inoculation. All pigs received a common diet from -14 to -7 DPI (1 weeks post-weaning) and were provided either the LSBM or HSBM diet starting at -7 DPI.
[2] Orthogonal contrasts of pigs fed LSBM vs. HSBM within the uninfected or PRRSV-infected groups.
[3] Pigs were allotted to final treatment groups at -7 DPI, and received experimental diets for a 1 week period prior to PRRSV inoculation.

Table 3. Effects of dietary soybean meal level and porcine reproductive and respiratory virus (PRRSV) infection on haptoglobin and cytokine production in weanlings pigs.[1]

						P-value				
	Uninfected		PRRSV-infected			Main effects		Diet ×	LSBM vs. HSBM[2]	
Item	LSBM	HSBM	LSBM	HSBM	SEM	Diet	PRRSV	PRRSV	Uninfected	PRRSV-infected
3 DPI										
HAP, µg/mL	979	1,311	2,163	1,363	262	0.36	0.02	0.01	0.36	0.03
TNFα, pg/mL	85.1	105.5	181.7	175.1	7.5	0.36	<0.01	<0.01	0.06	0.53
IL-1β, pg/mL	0.0	0.0	12.9	8.5	3.0	0.45	<0.01	<0.01	1.00	0.28
7 DPI										
HAP, µg/mL	1,180	864	2,062	1,657	262	0.16	<0.01	<0.01	0.38	0.26
TNFα, pg/mL	59.8	63.4	161.3	150.1	8.0	0.62	<0.01	<0.01	0.74	0.30
IL-1β, pg/mL	0.0	0.0	14.7	20.8	3.0	0.30	<0.01	<0.01	1.00	0.15
14 DPI										
HAP, µg/mL	263	315	1,860	1,857	283	0.93	<0.01	<0.01	0.89	0.99
TNFα, pg/mL	52.9	55.8	273.1	218.4	10.6	<0.01	<0.01	<0.01	0.79	<0.01
IL-1β, pg/mL	0.0	1.5	22.2	26.6	2.9	0.31	<0.01	<0.01	0.72	0.29

[1] Values represent least square means of 15 or 16 pigs. Abbreviations: LSBM = low soybean meal, HSBM = high soybean meal, DPI = days post-inoculation, HAP = haptoglobin, TNFα = tumor necrosis factor alpha, IL-1β = interleukin 1 beta.
[2] Orthogonal contrasts of pigs fed LSBM vs. HSBM within the uninfected or PRRSV-infected groups.

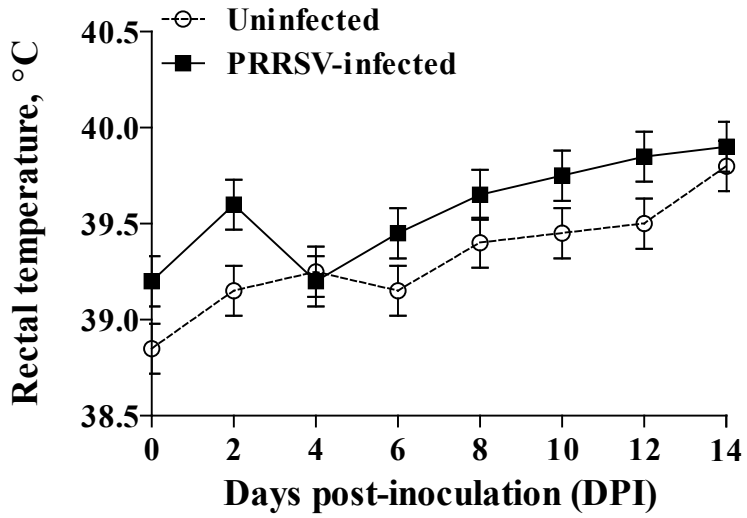

Figure 1. Rectal temperatures of uninfected or porcine reproductive and respiratory syndrome virus (PRRSV)-infected pigs during the 14 d infection period. Overall, rectal temperatures of PRRSV-infected pigs were higher ($P < 0.001$) than those of uninfected pigs during the infection period, with no effect ($P > 0.05$) of soybean meal inclusion level or interaction between soybean meal inclusion level and infection status.

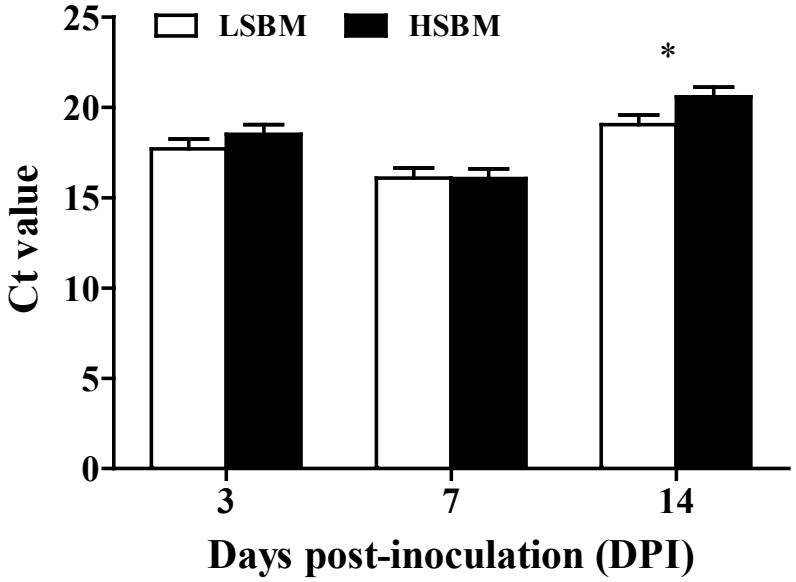

Figure 2. Serum viral load of porcine reproductive and respiratory syndrome virus (PRRSV)-infected pigs fed low (LSBM) or high (HSBM) soybean meal diets as determined by real-time reverse transcription PCR. Serum viral load is presented in cycle threshold (Ct) values, which are inversely related to the amount of viral RNA detected. Timing after inoculation influenced PRRSV load, with the greatest ($P < 0.01$) viral load observed at 7 DPI. There were no effects of diet ($P > 0.05$) on Ct values for pigs at 3 or 7 DPI. At 14 DPI, Ct values indicated that pigs fed HSBM had a lower ($P < 0.05$) viral load than pigs fed LSBM.
*Indicates a difference ($P < 0.05$) due to soybean meal inclusion on the specified DPI.

Nutritional and Functional Properties of Fiber in Swine Diets

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Summary

Fiber is not a well-defined chemical entity, but a term that in both human and animal nutritional literature has been defined by the method applied for its analysis; crude fiber, neutral and acid detergent fiber, and dietary fiber. In this paper, fiber is defined as non-starch polysaccharides and lignin, whereas the term dietary fiber is used for non-digestible oligosaccharides, resistant starch, non-starch polysaccharides, and lignin. The dietary fiber fraction represents the proportion of the feed that is not degraded by endogenous enzymes but is broken down to a variable extent by the microflora colonizing the different parts of the gastrointestinal tract. In the small intestine, non-digestible oligosaccharides are degraded to a larger extend than non-starch polysaccharide components. Fiber has a strong impact on the flow of ileal digesta and the digestibility of nutrients in the small and large intestine; for the total tract digestibility of organic matter and energy, insoluble fiber components are of special importance. Fiber is also the factor with the largest impact on the proportion of energy absorbed as glucose or short-chain fatty acids and thereby the overall energy utilization.

Introduction

Fiber is an important component of the diet for non-ruminant and ruminant species. Since the fiber fraction represents compounds of the feed with complex composition and structural proportions, it is considered a marker for low digestibility and nutrient utilization in most species. Consequently, the digestibility and the energy concentration of feedstuffs are lower for feedstuffs with higher fiber concentration compared with those with lower fiber content; e.g., metabolizable energy of wheat and barley are 95% and 86%, respectively, of corn. The fiber fraction, however, also possesses physicochemical properties which influence the lumen environment and which may interfere with the digestion and absorption processes at all sites of the gastrointestinal tract, and thereby potentially influence gastrointestinal health and animal welfare.

The main purpose of this paper is to give an overview of our current knowledge concerning the role of fiber in the nutrition of swine. The paper will address questions concerning terminology, definition and analysis of fiber, and the nutritional and functional properties of fiber in swine diets with emphasis on effects of fiber in the gastrointestinal tract and the influence on nutrient utilization.

Terminology and Definitions

Fiber is not a well-defined chemical entity, but a term that in both human and animal nutritional literature traditionally has been defined by the method applied for its analysis. Classically, the crude fiber method and the detergent methods of Van Soest and co-workers have been used for characterizing fibers in feeds and diets for swine (Van Soest, 1988). Inspired by the growing interest for fiber in human nutrition, enzymatic- or non-enzymatic gravimetric and enzymatic-chemical methods have been developed for the analysis of dietary fiber in foods. These methods have also been applied for the analysis of dietary fiber in feeds and diets for animal nutrition (Bach Knudsen, 1997; Theander et al., 1989).

The interest for fiber in human nutrition has inspired a continuous debate for more than a quarter of a century concerning the definition of dietary fiber (McCleary et al., 2012). Recently, Codex Alimentarius and the European Commission agreed on a physiological definition of fiber as: "carbohydrate polymers with ten (or three) and more monomeric units which are neither digested nor absorbed in the human small intestine and belonging to the following categories:

- edible carbohydrate polymers naturally occurring in food as consumed;
- edible carbohydrate polymers which have been obtained from food raw material by physical, enzymatic, or chemical means and which have a benefi-

cial physiological effect demonstrated by generally accepted scientific evidence;
- edible synthetic carbohydrate polymers which have a beneficial physiological effect demonstrated by generally accepted scientific evidence."

The difference between the European Commission and the Codex Alimentarius definition is the inclusion or not of non-digestible oligosaccharides. The new extended definition includes not only what classically is consider as dietary fiber, the sum of non-starch polysaccharides (**NSP**), and lignin, but also carbohydrate components with similar physiological/nutritional properties like fiber, i.e., resistant starch and non-digestible oligosaccharides, and has given rise to further method developments for the characterization of dietary fiber (McCleary et al., 2012). The use of a physiological definition for dietary fiber, however, has made it increasingly difficult to analyze all the dietary fiber components using just one analytical method. While neutral detergent fiber in many feedstuffs is reasonably closely related to insoluble dietary fiber (Bach Knudsen et al., 2013), the relationship between dietary fiber and the neutral detergent fiber is not as strong.

In animal nutrition, we have not yet an agreed definition of dietary fiber, but the conventional thinking of fiber is more as NSP plus lignin rather than the extended definition of dietary fiber. In the following, the term **dietary fiber** will be used for the extended definition and **fiber** for NSP plus lignin.

Chemistry

Cell wall polysaccharides

Fiber is primarily found in the plant cell wall (McDougall et al., 1996) (Figure 1, Table 1). The plant cell wall consists of a series of polysaccharides often associated and/or substituted with proteins and phenolic compounds and in some cells together with the phenolic polymer lignin (Theander et al., 1989). The building blocks of the cell wall polysaccharides are the pentoses arabinose and xylose, the hexoses glucose, galactose and mannose, the 6-deoxyhexoses rhamnose and fucose, and the uronic acids glucuronic and galacturonic acids (or its 4-O-methyl ether). Although the cell wall polysaccharides are built from only 10 common monosaccharides, each monosaccharide can exist in two ring (pyranose and furanose) forms, and these residues can be linked through glycosidic bonds at any one of their three, four, or five available hydroxyl groups and in two (α or β) orientations. As a result, cell wall polysaccharides can adopt a huge number of three-dimensional shapes and thereby offer a vast range of functional surfaces (McDougall et al., 1996). The NSP can also be linked to lignin and suberin which provide hydrophobic surfaces and which stiffen the walls, thus preventing biochemical degradation of the walls.

The most important cell wall polysaccharide is cellulose that forms a network of cellulose microfibers (Figure 1). Cellulose is present in all cell walls of both mono- and dicotyledonous plants. For the other cell walls, there is a distinct difference between mono- and dicotyledonous plants, as mixed linkage β-glucan and arabinoxylan are the main cell wall polysaccharides of cereals, whereas xyloglucans, gluco- and galactomannans, and pectic polysaccharides (arabinogalactans, pectins, etc.) are the main cell wall polysaccharides of protein rich seeds and grains (Bach Knudsen, 2014). These polysaccharides together with cellulose are present in various proportions in the different types of cell walls, depending on the function of the cell walls within the tissues.

Non-cell wall polysaccharides

Some plant materials also contain intracellular NSP as storage carbohydrates such as fructans in Jerusalem artichoke and chicory roots and mannans in palm and coconut cake. In contrast to the plant cell wall, lignin is not associated to storage NSP.

Fiber feed additives

A number of purified soluble and viscous and non-viscous polysaccharides such as pectins of different origin, inulin, alginates, carrageenans, gum xanthan, guar gum, or gum arabic (acacia) as well as carboxymethylcellulose and insoluble polysaccharides such as cellulose are frequently used as feed additives in studies with pigs. The practical use of these polysaccharides, however, is limited.

Resistant starch

Native starch is a semi-crystalline material synthesized roughly as spherical granules in many plant tissues of which cereals and pulses (peas and beans) are the most important feedstuffs in pig nutrition. Pure starch consists predominantly of α-glucan in the form of amylose and amylopectin. Amylose is a linear α(1-4)- linked molecule, while amylopectin is much larger, heavily branched by α(1-6)- linkages. The two α-glucans are present in various proportions in the starch granules; amylopectin forms a branched helical crystalline system interspersed with amorphous lamella. Although all starch potentially can be digested by α-amylase and the brush-border enzymes in the small intestine (Gray, 1992), a certain fraction of starch will resist enzymatic digestion in the small intestine, either because

it is trapped within whole plant cells matrices (resistant starch, RS_1), the starch granules are resistant (RS_2), the starch is retrograded (RS_3), or the starch is chemically modified (RS_4) (Englyst et al., 1992).

Non-digestible oligosaccharides

Non-digestible oligosaccharides are naturally present in a number of predominantly protein rich feedstuffs such as α-galactosides - raffinose, stachyose, verbascose, and ajugose - or as fructooligosaccharides as in the fructan fraction in Jerusalem artichoke and chicory roots. Non-digestible oligosaccharides may also be incorporated into the pig's diet as isolates of fructooligosaccharides from partly hydrolyzed inulin or enzymatically synthesized as trans-galactooligosaccharides or as xylo-oligosaccharides.

Lignin

Lignin is formed by the polymerization of coniferyl, *p*-coumaryl, and sinapyl alcohols (Davin et al., 2008). These phenylpropane units are linked by an irregular three-dimensional pattern of ether and carbon-carbon bonds, in which either of the carbons may be part of the aromatic ring. Lignin may be covalently linked to polysaccharides both directly through sugar residues and indirectly via ferulic acid esterified to polysaccharides (Davin et al., 2008). Lignin tends to fixate the polymers and will consequently cement and anchor the cellulose microfibrils and other matrix polysaccharides and in this way stiffen the walls making them very rigid and difficult to degrade by the microorganisms in the large intestine.

The Analysis Fiber

The analysis of the diverse group of substances that make up the fiber fraction requires a range of analytical techniques for complete characterization. Commonly used methods as illustrated schematically in Figure 2 include enzymatic or chromatographic methods to determine oligosaccharides, enzymatic methods to determine resistant starch, and gravimetric or enzymatic-chemical methods to determine soluble, insoluble, and total dietary fiber (Bach Knudsen, 1997).

Since the different analytical methods used for the determination of fiber vary widely in terms of analytical principles, the values reported in the literature will vary too. The values reported with the enzymatic-chemical method are higher than those reported by the detergent methods developed by Van Soest and co-workers and are much higher than what is reported with the crude fiber method (Bach Knudsen et al., 2013).

Physicochemical Properties of Fiber

The physicochemical properties—hydration and viscosity—of fiber are linked to the type of polymers that makes up the cell wall and their intermolecular association (McDougall et al., 1996). The hydration properties are characterized by the swelling capacity, solubility, water holding capacity, and water binding capacity. The latter two have been used interchangeably in the literature, since both reflect the ability of a fiber source to immobilize water within its matrix. The first part of the solubilization process of polymers is swelling, in which incoming water spreads the macromolecules until they are fully extended and dispersed. Imagine how the cell wall in Figure 1 expands in the three dimensional space (Thibault et al., 1992), and the soluble polysaccharides are released from the matrix and into the liquid phase, and how water is trapped in the cell wall matrix (Figure 3). Solubilization is not possible in the case of polysaccharides that adopt regular, ordered structures (e.g., cellulose), because the linear structure increases the strength of the non-covalent bonds which stabilize the ordered conformation. Under these conditions, only swelling can occur (Thibault et al., 1992).

Fiber and Physicochemical Properties of Feedstuffs

The modern pig industry relies on relatively few feedstuffs, primarily from cereals (rice, corn, sorghum, wheat, rye, triticale, barley, and oats); cereal co-products (different milling fractions, residues from alcohol industry, residues from bioethanol production, etc.); cereal substitutes (tapioca, maniocca); protein concentrates, including meal or cakes of soybean, rape, sunflower, cotton, lupins, peas, and beans; and fiber-rich co-products (dried pulp from the sugar and starch industries). Roughages, fresh roots, and tubers, in contrast, are only used occasionally and primarily for the feeding of sows or as feeds in organic farming. Fiber values for common feedstuffs and analyzed by different methods are shown in Table 2. There is a close relationship between fiber and dietary fiber with the latter higher than the former because of the inclusion of non-digestible oligosaccharides, fructans and resistant starch. Neutral detergent fiber is reasonably closely related to the insoluble fiber components (insoluble non-cellulosic polysaccharides, cellulose and Klason lignin), whereas the values for acid detergent fiber and crude fiber are significantly lower than the fiber and dietary fiber values.

The physicochemical properties of some selected feeds are shown in Table 3. Fiber sources containing pectins, i.e., pea cotyledon, potato pulp, and sugar beet pulp, swell and hold water to a larger extent than is the

case with hulls primarily because the presence of the pectin components in the cell walls and the low level of lignin make the cell walls more elastic and capable of expanding in the three dimensional space (Figures 1 and 3).

Fiber and the Digestion and Absorption Processes

The gastrointestinal tract consists of different compartments—mouth, stomach, small intestine, and large intestine - and supplying organs - liver, pancreas - involved in the digestion and absorption processes. The predominant degradation processes taking place in stomach and small intestine are by endogenous enzymes that degrade the nutrients that potentially can be hydrolysed by the secreted carbohydrases, proteases, and lipases, whereas microbial enzymes dominate the hydrolytic activities in the large intestine. The whole assembly is furthermore integrated with the peripheral organs through a large set of receptors (distension, tactile, chemo) that monitor the digestive and absorptive processes through neural and hormonal feedback signals. In this way variations in blood nutrient content are minimized and the provision of nutrients to the different organs regulated and optimized.

Small intestine

The only carbohydrates secreted by pigs are salivary and pancreatic α-amylases which digest α-(1-4)-glucosidic linkages as in starches (Gray, 1992). The majority of starch is degraded by pancreatic α-amylase in the intestinal lumen with the end products: maltose, maltotriose, and α-limit dextrins. These oligosaccharides are further degraded to glucose by α-glucosyl saccharidases located on the intestinal surface membrane, where sucrase and lactase are also present. A contributing carbohydrate hydrolytic effect, however, comes from the microflora permanently colonizing these sites of the gastrointestinal tract. Jensen and Jørgensen (1994) reported a gradual increase in total anaerobic bacteria from 10^7 to 10^9 viable counts in stomach to 10^9 viable counts in distal small intestine. Substantial levels of lactic acids and short-chain fatty acids (SCFA) have also been reported in digesta collected from the stomach and the more distal parts of the small intestine.

Because of the contributing carbohydrate hydrolytic activity from the microflora in stomach and small intestine, it is not surprising to find a significant degradation of dietary fiber components; around 40% for non-digestible oligosaccharides and 20-25% for NSP (Bach Knudsen et al., 2013). Nevertheless, the concentration of NSP increases substantially from ingestion (diet) to the end of the small intestine, as the digesta are depleted of digestible nutrients (sugars, starch, protein, and fat) (Table 4). Likewise, the flow of digesta increases in response to the dietary fiber level, as will the viscosity and water binding capacities (Figure 3). The ability to do so depends on the chemical and structural compositions of the dietary fiber fraction. However, although the dietary fiber level has a profound influence on the digesta flow, neither soluble nor insoluble dietary fibers have any major impact on the digestibility of starch (Table 5) (Bach Knudsen et al., 2006). Rather, the main factor influencing the digestibility of starch in the gastrointestinal tract is the physical structure of the starch; i.e., the digestibility of starch from raw potato starch (Type B) and raw legume starch (Type C) is generally lower than that of cereal starches (Type A) (Bach Knudsen et al., 2013; Bach Knudsen et al., 2006).

Taken as a whole, fiber is the dietary constituent with the most significant negative effect on the ileal digestibility of organic matter (**OM**) and the apparent ileal digestibility of protein. Based on calculations of 78 diets (Bach Knudsen et al., 2013), the relationship can be expressed as:

Ileal digestibility of OM = $95.1 - 0.135 \times$ fiber, $R^2 = 0.77$

Apparent ileal digestibility of protein
= $88.0 - 0.095 \times$ fiber, $R^2 = 0.28$

The reason for the negative association between fiber and the digestibility of protein should be found in the encapsulation of nutrients within intact cell walls that hinders the enzymatic degradation in the small intestine as demonstrated in studies with oat bran (Figure 4). A contributing factor in the negative effect of fiber on the apparent ileal digestibility of protein is the high viscosity and water binding capacities of high fiber diets which enhances the secretion of endogenous nitrogen.

Large intestine

The large intestine of pigs is characterized as dark, warm, moist, anaerobic, and filled with feed residues that flow at a relatively low speed. These are all conditions that favor the growth of microorganisms which in numbers can reach 10^{11}-10^{12} per gram (Jensen and Jørgensen, 1994). The microbial ecosystem thus contains hundreds of species of anaerobic bacteria, with each species occupying a particular niche and with numerous interrelationships between them (Louis et al., 2007). The outcome of this fermentation is production of short-chain fatty acids (**SCFA**) which is absorbed to the portal vein by passive diffusion (Bergman, 1990) and by the gases that are excreted through flatus and the

expiration (Jensen and Jørgensen, 1994). Although the luminal production of SCFA can increase several fold in response to the dietary composition, the concentration of SCFA in the large intestine is remarkably similar; i.e., the rate of absorption is in balance with the luminal production rate (Bergman, 1990).

Bacteria that colonize the large intestine have access only to the dietary residues that escape digestion in the small intestine. The range of carbohydrates that arrive in the large intestine from the diet is enormous and variable depending on the dietary composition. With most diets, NSP represent the major carbohydrate fraction entering the large intestine (Table 5). These polymers arrive in various states and with varying solubility, chain length, and association to other molecules. The rate and overall degree of degradation of dietary fiber components in the large intestine are influenced by the chemical nature, the solubility, and the degree of lignification (Figure 5). Examples of rapidly degradable fiber components are β-glucan, soluble arabinoxylan, and pectins which are all degraded in the caecum and proximal colon, while cellulose and insoluble arabinoxylan and other insoluble non-cellulosic polysaccharides are degraded more slowly at more distal locations. From an analysis of the relationship between the fiber level and the total tract digestibility of OM (and energy) and the apparent digestibility of protein (Bach Knudsen et al., 2013), the following relationship was established:

Total tract digestibility of OM = 101.0 – 0.09 × fiber, $R^2 = 0.70$

Apparent total tract digestibility of protein
= 97.0 – 0.094 × fiber, $R^2 = 0.61$

It is primarily the insoluble fiber components such as cellulose, insoluble non-cellulosic polysaccharides, and lignin that resist microbial degradation and thereby contribute to the bulk in colon and increase in fecal dry weight (energy) (Figure 6). The stimulation of the growth of the microflora by all non-digestible carbohydrates will also contribute to an increase in fecal wet and dry weight although to a lower extent. In contrast, fermentable dietary fibers will increase SCFA production, and lower the pH in the large intestine.

Influence of Fiber on the Site of Nutrient Digestion and Utilization

The importance of the fiber concentration of the quantitative digestion of nutrients in ileum and in the total tract is illustrated by the data in Table 5. The bulk of sugars (close to 100%), starch (97%), protein (75%), and fat (72%) disappear during the passage of the small intestine. Of the OM that arrives in the large intestine, approximately half of it is fermented as it passes along the large intestine but with substantial differences between the nutrients; 37% of crude protein, 59% of NSP, 71% of non-identified residues, and 90% of starch disappear, whereas there is no net degradation of fat. It can also be depicted from the table that the amount of organic residues degraded in the large intestine increases in response to the fiber concentration; i.e., the degradation is 170 g OM/d when a diet with a fiber level of 150 g/kg DM is fed, whereas 286 g OM/d is degraded when the fiber concentration is 200 g/kg DM. For sows fed diets with 429 to 455 g/kg DM of fiber, the degradation of OM can reach levels of 355 to 503 g/d (Serena et al., 2008).

The amount of carbohydrates that passes from the small to the large intestine has a profound influence on the nature of the absorption of products, because the portal flux of SCFA increases (r = 0.90) and that of glucose decreases (r= -0.70) in response to more carbohydrates being fermented in the large intestine (Table 6). With the low dietary fiber maize starch diets, only ~4% of absorbed energy derives from SCFA, while it was 44% when the high dietary potato diet was fed. An even higher energy contribution from SCFA was seen in sows that were fed a high-fiber diet with 429 g/kg DM fiber and where 52% of the energy derived from SCFA compared with 12% in a low-fiber diet containing 177 g/kg DM fiber (Serena et al., 2009).

High-fiber diets will have a lower digestibility of energy, a lower content of metabolizable energy, and a lower utilization of the metabolizable energy. The reason is that the efficiency of SCFA absorbed from the large intestine is lower than of glucose absorbed in the small intestine; the efficiency of SCFA is 69% of glucose. The difference is due to losses of energy in H_2 and CH_4, increased fermentation heat, and a lower utilization of SCFA in the intermediary metabolism.

Conclusion and Implications

Fiber represents components of the feed with complex composition and structural properties with great impact on the physicochemical properties of digesta, the digestibility of nutrients in the different parts of the gastrointestinal tract, and nutrient utilization. The physiochemical properties of the fiber in the gastrointestinal tract and the interaction of the different dietary fiber components with the microbiota may potentially influence the health of the animals by making them more robust for digestive disturbances. A further implication of the fiber is the influence on nutrient absorption; fiber rich diets will be retained in the stomach for a longer time and the nutrients taken up more slowly from the gastrointestinal tract thereby potentially influencing the behavior of the animals.

Table 1. Dietary fiber components in feedstuffs and feed additives.

Category	Monomeric residues	Examples of source
Non-digestible oligosaccharides (DP 3-9)		
α-galactosides		
(Raffinose, stachyose, verbascose)	Galactose, glucose, fructose	Soybean meal, peas, rape seed meals etc.
Fructo-oligosaccharides	Fructose	Cereals, feed additives
Trans-galactooligosaccharides	Galactose, glucose	Feed additives
Xylo-oligosaccharides	Xylose, arabinose	Feed additives
Polysaccharides (DP≥10)		
A. Resistant starch (RS)		
Physical inaccessible—RS1	Glucose	Peas, faba beans
Native—RS2	Glucose	Potato
Retrograded—RS3	Glucose	Heat treated starch rich products
Chemically modified—RS_4	Glucose	Chemically modified starch
B. Non-starch (NSP)		
Cell wall NSP		
Cellulose	Glucose	Most feedstuffs
Mixed linked b-glucans	Glucose	Barley, oats, rye
Arabinoxylan	Xylose, arabinose	Rye, wheat, barley, cereals by-products
Arabinogalactans	Galactose, arabinose	Cereal flours
Xyloglucans	Glucose, xylose	Pea hulls
Rhamnogalacturans	Uronic acids, rhamnose	Soybean meal, sugar beet fiber/pulp
Galactans	Galactose	Lupins
Non-cell wall NSP		
Fructans	Fructose	Jerusalem artichoke, chicory roots, rye
Mannans	Mannose	Coconut cake, palm cake
Pectins	Uronic acids, rhamnose	Feed additives
Guar gum	Galactose, mannose	Feed additives
Lignin	Phenylpropanoid	Barley hulls, oat hulls,

DP, degree of polymerization; RS, resistant starch; NSP, non-starch polysaccharides.

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Table 2. Typical values for dietary fiber components (g/kg DM) in feedstuffs.

	Non-digestible carbohydrates											
Feedstuff	**OS**	**Fructans[1]**	**RS**	**S-NCP[2]**	**I-NCP[3]**	**Cellulose**	**KL**	**Fiber[4]**	**Dietary[5] fiber**	**NDF**	**ADF**	**Crude Fiber**
Rice	2	<1	3	9	1	3	8	22	27	12	8	3
Corn	3	6	10	9	66	22	11	108	127	101	33	25
Wheat	6	15	4	25	74	20	19	138	163	101	38	28
Barley	6	4	2	56	88	43	35	221	233	160	63	52
Oats	5	3	2	40	110	82	66	298	308	223	119	107
Wheat bran	16	20	2	29	273	72	75	449	487	370	123	101
Barley hulls	12	7	2	20	267	192	115	594	615	539	247	221
DDGS—corn	ND	ND	ND	25	183	68	47	323	323	ND	ND	ND
DDGS—wheat	ND	ND	ND	55	135	61	86	337	337	ND	ND	ND
Peas	49	ND	22	52	76	53	12	192	263	146	83	65
Faba beans	54	ND	32	50	59	81	20	210	296	159	113	89
Soybean meal	60	ND	ND	63	92	62	16	233	293	153	121	77
Rape seed cake	16	ND	ND	43	103	59	90	295	311	228	209	128
Cotton seed cake	54	ND	ND	61	103	92	83	340	394	276	194	156
Pea hull	ND	5	ND	121	148	452	9	677	682	ND	ND	ND
Potato pulp	ND	ND	127	280	95	202	35	612	739	ND	ND	ND
Sugar beet pulp	ND	0	ND	290	27	203	37	737	737	503	150	207
Chicory roots	ND	470	ND	76	24	48	11	158	628	ND	ND	ND

Klason lignin; NDF, neutral detergent fiber; ADF, acid detergent fiber; ND, not determined.
1 Fructans are a mix of oligosaccharides (DP 3-9) and polysaccharides (DP>10).
2 S-NCP is synonymous with soluble fiber.
3 The sum of I-NCP, cellulose, and KL is insoluble fiber.
4 The sum of S-NCP, I-NCP, cellulose, and KL is fiber.
5 The sum of OS, Fructans, RS, S-NCP, I-NCP, cellulose KL is dietary fiber.
Data from Bach Knudsen (1997) and unpublished.

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Table 3. Fiber content, swelling and water binding capacities of selected feedstuffs.

Feedstuff	**Fiber g/kg DM**	**Swelling L/kg DM**	**Water binding capacity kg/kg DM**
Wheat	128	2.9	1.2
Barley	217	4.0	1.5
Dehulled barley	160	5.0	1.3
Barley hulls	540	6.3	2.6
Pea cotyledon	485	11.3	7.6
Pea hull	857	6.1	3.6
Potato pulp	612	10.8	7.2
Sugar beet pulp	737	8.7	8.7

Table 4. Digesta flow, marker index, and concentrations of carbohydrates in diet and ileal digesta.

Item	Digesta flow, g/d	Marker index	Dig CHO		DF	
			Sugars	Starch	Fructans	NSP
Growing pigs						
Low dietary fiber						
Diet		100	6	517	-	56
Ileum	2,126	652	7	17	-	366
Medium dietary fiber						
Diet		100	7	454	-	97
Ileum	2,584	472	8	12	-	372
High dietary fiber						
Diet		100	29	492	14	211
Ileum	3,785	345	8	28	20	514
Adult sows						
Low dietary fiber						
Diet		100	21	501	9	140
Ileum	5,560	347	10	59	3	267
High dietary fiber						
Diet		100	23	210	6	363
Ileum	9,816	187	3	33	1	507

Dig, digestible; CHO, carbohydrates; DF, dietary fiber; NSP, non-starch polysaccharides.
Data compiled by Bach Knudsen et al. (2013).

Table 5. Intake and recovery of nutrients (g per day) at ileum and in feces and the effects of fiber on the recovery of nutrients at ileum and in feces.

	Intake	Recovery Ileum	Effect of fiber			Recovery Feces	Effect of fiber		
			Intercept	Slope	R^2		Intercept	Slope	R^2
Dry matter	2,000	536	113	3.1	0.75	273	-25	2.2	0.79
Organic matter	1,903	475	88	2.8	0.78	231	-38	2.0	0.80
Protein (N×6.25)	351	88	39	0.4	0.29	56	10	0.34	0.65
Fat	130	36	25	0.1	0.06	35	21	0.1	0.15
Carbohydrates:									
Sugars	99	NS[1]				NS[1]			
Starch	984	31	13	0.11	0.08	3	-1	<0.1	0.15
Non-starch polysaccharides	244	191	5	1.3	0.76	79	-49	0.9	0.69
Lignin[2]	36	36[2]	-2	0.3	0.54	36[2]	-2	0.27	0.34
Residue	59	100	6	0.7	0.31	29	-16	0.3	0.21

The data in this table were compiled from 21 published and one unpublished articles representing 78 diets. The intake was calculated based on 2,000 g of dry matter and converted to macronutrients from the reported chemical compositions. The recoveries at ileum and in feces were calculated based on the digestibility coefficients reported in the papers (Bach Knudsen et al., 2013).

[1] NS, not measured. Sugar residues in ileum and feces will be part of the residue fraction.

[2] It is assumed that lignin is not broken down during passage of the gut.

Table 6. Effects of meal size and intake of digestible starch and non-digestible carbohydrates on portal concentrations and fluxes of glucose and short-chain fatty acids, and the proportion of energy absorbed as glucose and short-chain fatty acids.

	Intake, g				Glucose		SCFA		Absorbed energy, %	
	Meal	Dig.	Dietary fiber							
Diet	Size	Starch	RS	NSP	mmol/L	mmol/h	mmol/L	mmol/h	Glu	SCFA
LF wheat bread	1,300	746	4	77	8.10	175	775	30	93.0	7.0
HF wheat bran	1,300	663	3	140	7.69	127	854	30.8	90.5	9.5
HF oat bran	1,300	605	3	140	7.66	132	908	37.1	89.1	10.9
HF Rye bread	1,250	676	13	254	6.60	157	1,140	76.9	82.4	17.6
HF Wheat bread	1,250	610	7	275	6.43	117	1,001	66.5	80.2	19.8
Maize starch	860	536	9	39	8.85	146	459	13.9	96.0	4.0
Pea starch	860	535	15	36	6.90	105	454	17.8	93.1	6.9
Maize starch	1,250	762	20	66	8.14	185	480	19.1	95.7	4.3
Maize:potato (1:1) starch	1,250	609	189	66	6.94	109	1,240	60.3	90.6	19.4
Potato starch	1,250	361	458	66	5.97	49	1,620	88.9	55.9	44.1

SCFA, short-chain fatty acids; RS, resistant starch; NSP, non-starch polysaccharides, Glu, glucose; LF, low fiber; HF, high fiber.
Data compiled by Bach Knudsen et al. (2013).

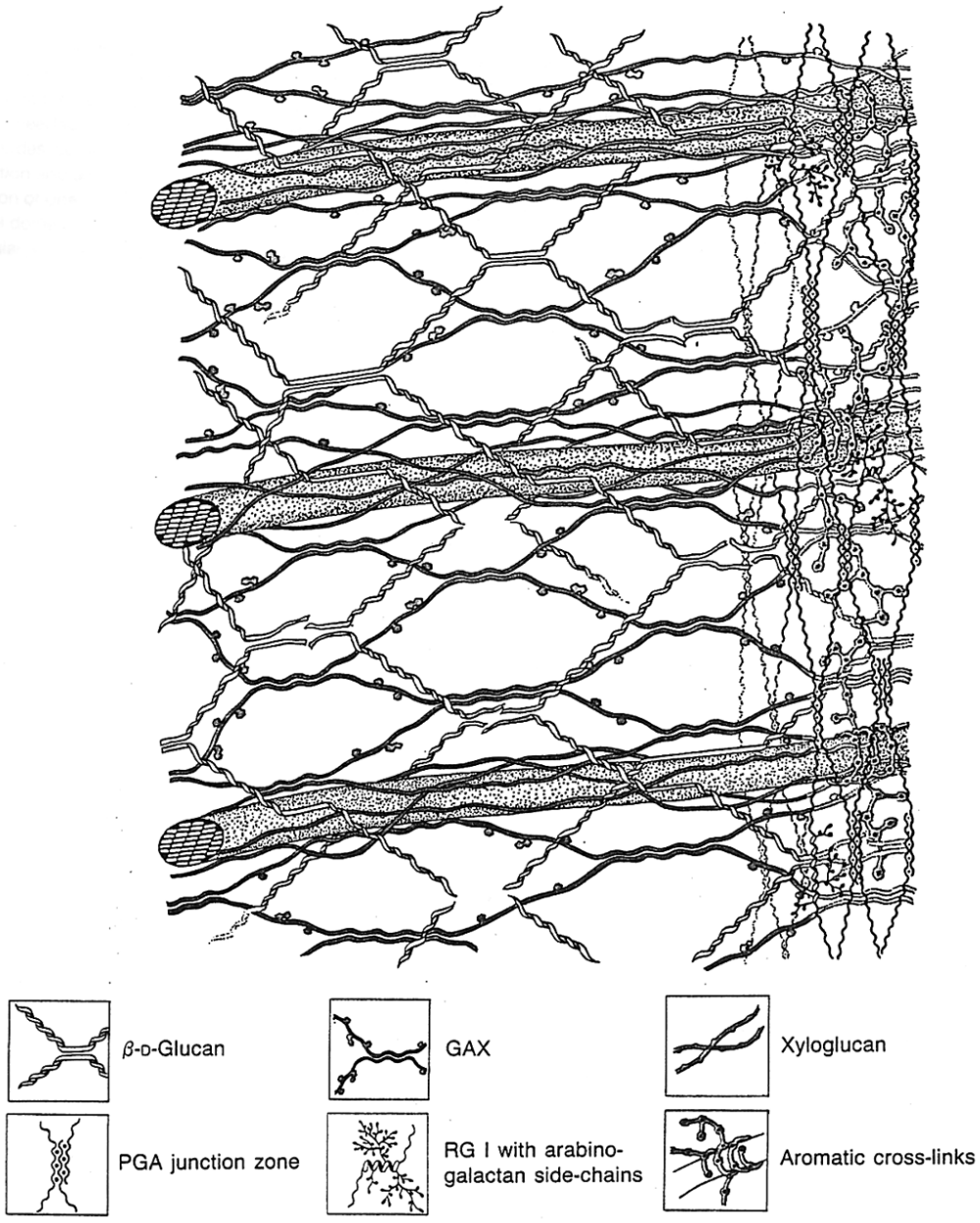

Figure 1. Cell wall model showing cellulose fibrils interlocked by glucurono-arabinoxylans (GAX). Some of the GAX are "wired" onto the cellulose fibrils by phenolic linkages, whereas the substituted parts of GAX block hydrogen bonding. Small amount of pectic substances (PGA, RG1) are also present.

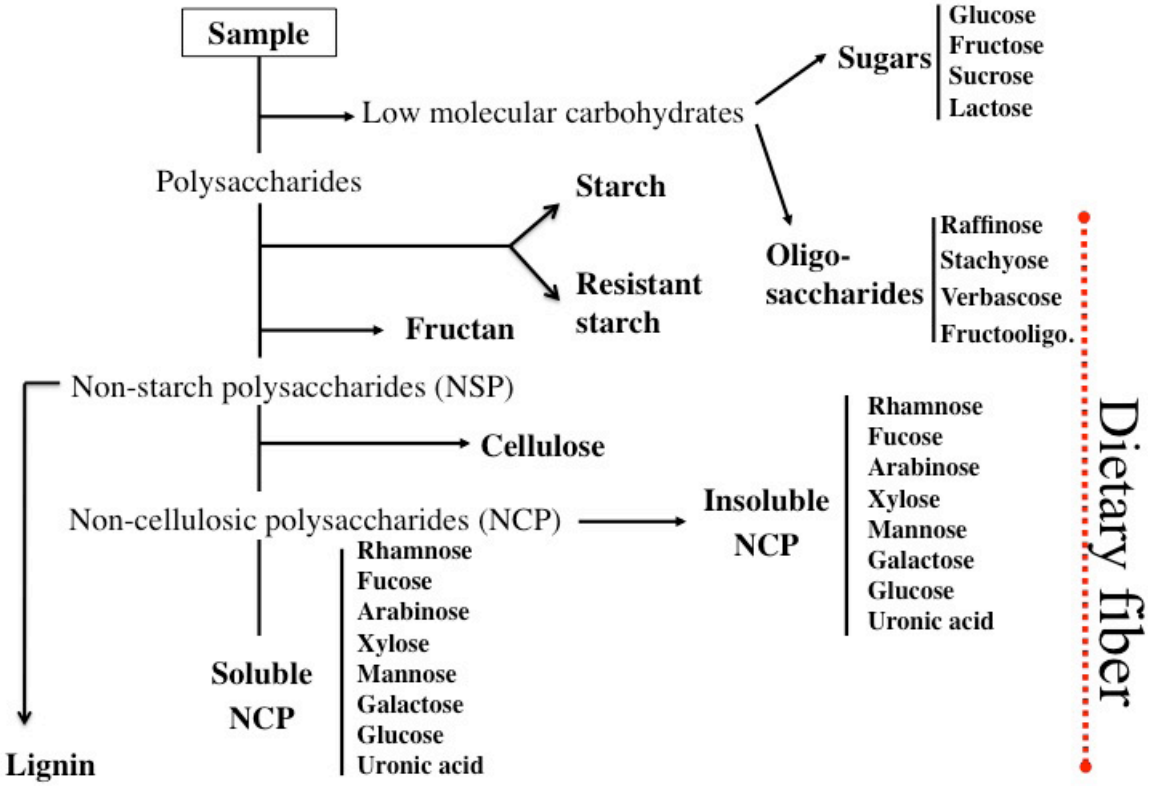

Figure 2. The principles in the classification of dietary fiber and other carbohydrates in feedstuffs.

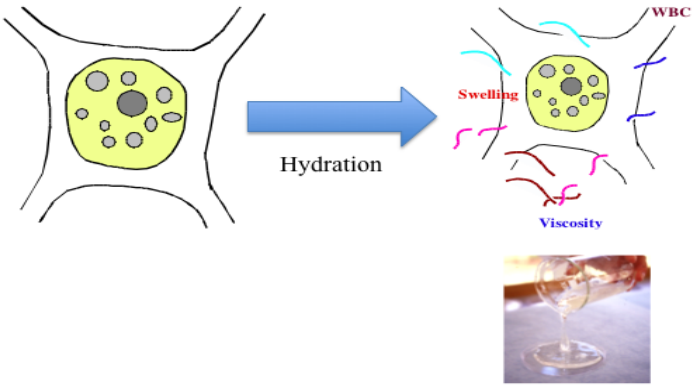

Figure 3. The hydration process of fiber. Incoming water spread the macromolecules which expand in the fiber matrix in the three dimensional space. During this process, some of the polysaccharides will be solubilized from the fiber matrix and thereby increase the viscosity of the liquid phase.

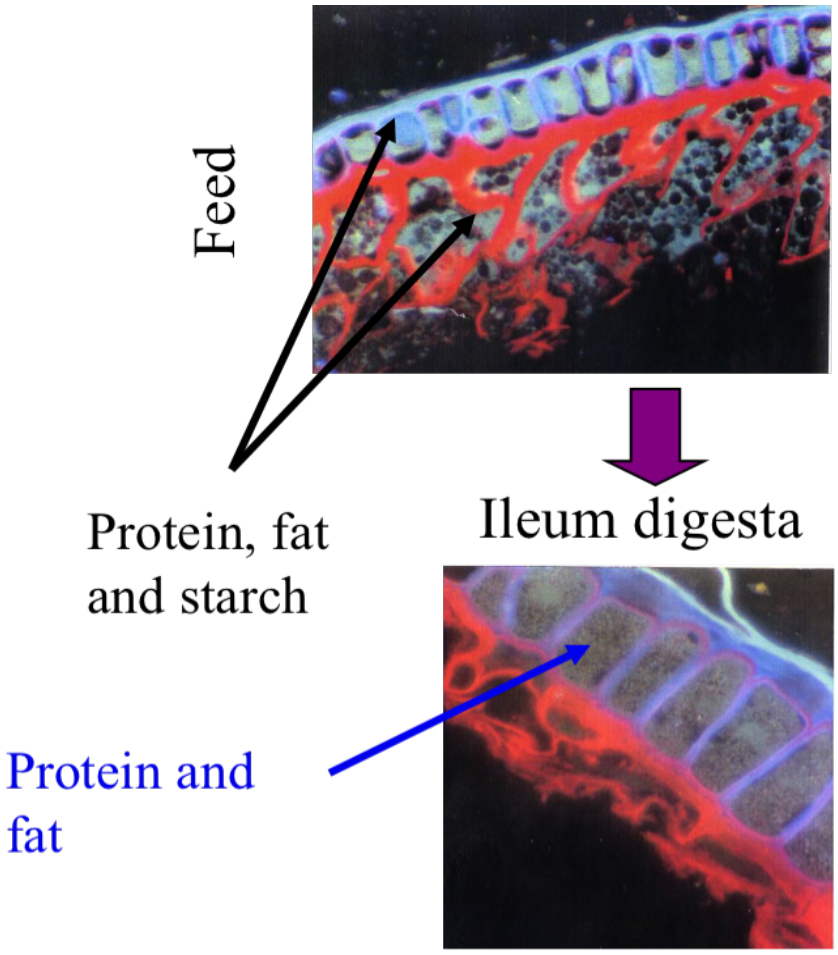

Figure 4. Example of encapsulation of nutrients within cell structure. The feed illustrates the subaleurone (red cell walls) and aleurone (blue cell walls) in the feed after passage of the small intestine. In ileal effluent, the aleurone cell walls encapsulate potentially available nutrients, i.e., protein and fat.

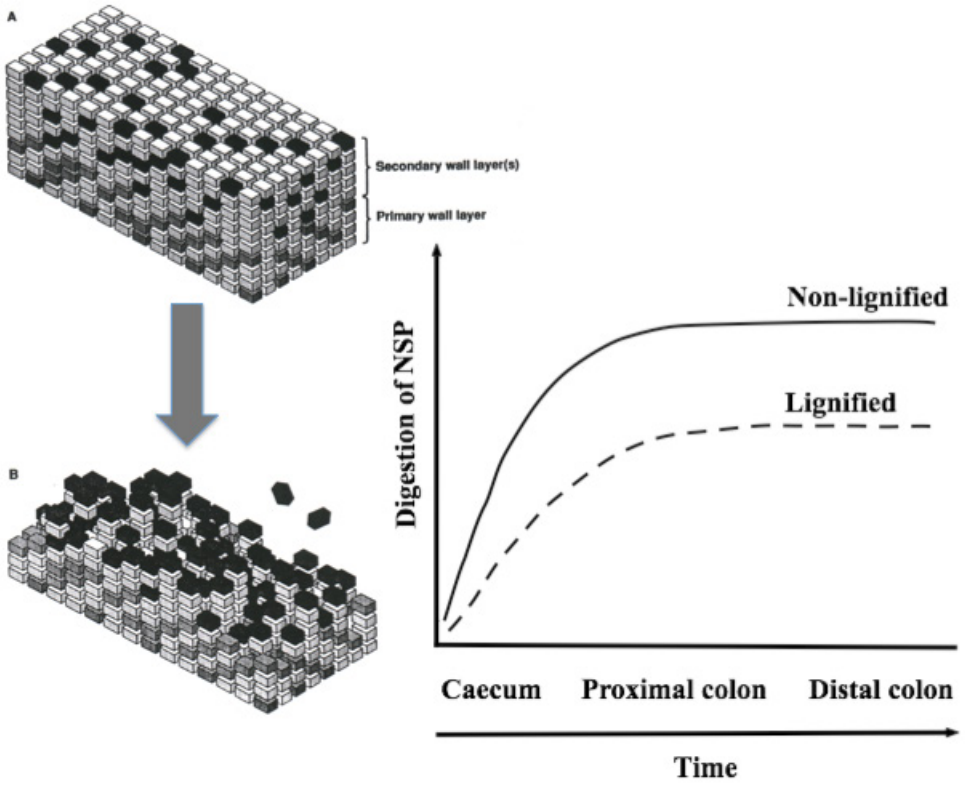

Figure 5. Exemplification of the degradation of non-starch polysaccharides (NSP) in non-lignified and lignified cell walls. In non-lignified cell walls, the degradation is rapid and almost complete, whereas in the lignified cell walls, the degradation is incomplete, because the lignin cross-link the cell wall polysaccharides. At a certain stage, the lignin makes further degradation impossible because non-degradable lignin hinders the access of the microorganisms to cell non-starch polysaccharides.

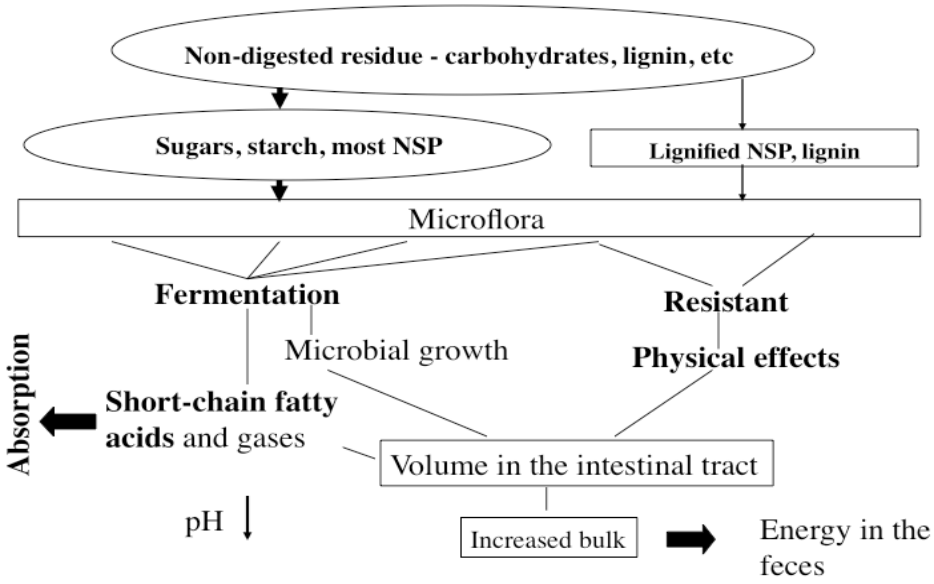

Figure 6. Schematic illustration of carbohydrate degradation in the large intestine and influence on colonic and fecal weight, bulk and energy. NSP = non-starch polysaccharides.

Effects of Decreasing Net Energy in Grow-Finish Diets with or without Paylean

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Summary

The use of lower cost by-products are constantly being evaluated or re-evaluated for their maximum inclusion rates in swine diets and what limitations (anti-nutritional factors, palatability, digestibility, etc.) they have across all phases of swine production. Successful use of by-products as an alternative to more expensive feed options is primarily dependent upon a pig's ability to utilize the nutrients available in the by-products to maintain a similar growth rate. Part of this change in the U.S. swine industry feeding practices is to move toward formulating diets on a net energy (NE) basis, which will be better at predicting the pig's ability to use these by-products. We conducted a study to look at the pig's ability to adapt to a low NE diet with increasing amounts of by-products and fiber in the diet and the interaction that may occur when ractopamine (RAC) is fed for the last 21 days prior to harvest. Low NE diets reduced growth rate (4%), feed efficiency (2.2%), and carcass weights and yields, but, feeding RAC improved pig growth performance regardless of dietary NE. The NE conversion to carcass weight was similar between NE diets and was improved by feeding RAC.

Introduction

The swine feed industry has faced some dramatic changes to our "typical" U.S. diet feeding programs with multiple droughts, high mycotoxins in some grains and grain by-products, and our traditional energy sources being diverted to ethanol and biodiesel production over the past several years, leaving us more by-products from many industries to feed and still try to remain profitable. In the U.S., high energy feed ingredients have been directed towards bioenergy production (i.e., corn to ethanol and animal fats to biodiesel) as part of a federal mandate to produce more renewable energy here in the U.S. This has resulted in the formulation of diets that are more diverse and with decreased energy concentration and current discussions of the optimal utilization of high fiber feed ingredients in the United States (Kerr and Shurson, 2013; Lindberg, 2014).

Diets with high by-product inclusion rates often have decreased energy concentrations and increased fiber content which may reduce the lipid accretion rates to a greater extent than protein accretion in grow-finish pigs. The lean gain of young pigs may be limited by their energy intakes from approximately 20 to 50 kg body weight (**BW**) (Schinckel and de Lange, 1996). However, the energy intakes of barrows above 90 kg BW may be greater than what is needed for maximal protein accretion (Campbell and Taverner, 1988). Therefore, a small reduction in daily energy intake of barrows in the latter half of the grow-finish period may improve their efficiency of energy utilization due to reduced fat deposition. One of the disadvantages to diets with increased fiber concentrations is their effect to reduce carcass weight gain by reducing dressing percentage or increased gut fill (Kennelly and Aherne, 1980; Pond et al. 1988). Ractopamine (**RAC**) is a feed additive that increases carcass lean gain and dressing percentage (Apple et al., 2007b, Schinckel et al., 2003). It is possible that the feeding of RAC the last 21 days (**d**) prior to market may result in increased carcass weights in pigs previously fed low energy- high fiber diets. In consideration of these changing feed dynamics, a grow-finish pig experiment was conducted with 3 objectives; 1) to evaluate a modern genetic line's ability to adapt to increasing amounts of by-product/higher fiber feed ingredients, 2) calculate the pig's conversion efficiency on a net energy (**NE**) basis of dietary energy into both live and carcass weight, and 3) to quantify the change in manure generation and nutrient output with higher by-product diets. This paper will only discuss the first 2 of these objectives from this experiment.

Materials and Methods

A total of 200 crossbred barrows (TOPIGS Tempo x TOPIGS 20) were blocked by BW (28.4 ± 0.02 kg), housed 5 barrows/pen and were randomly allocated to 1 of 4 treatments (10 pens/treatment) in a 2 x 2 factorial arrange-

ment, with 2 NE levels: Control vs. Low (**LE**) and with or without 7.5 ppm RAC hydrochloride during the last 21 d of the 105-d feeding trial. Pens (1.83 m x 2.44 m) were over totally slatted concrete floors with ad libitum access to a single hole self-feeder and nipple waterer.

There were five 21-d dietary phases (Grower 1-3, Finisher 1, and Finisher 2 with or without RAC). The diets were formulated on equal standardized ileal digestible (**SID**) lysine:NE ratio (Table 1 and 2) for each phase using ingredient nutrient values from National Swine Nutrition Guide (2010) or the Swine NRC (2012) and previously determined lysine requirements for this genetic line (TOPIGS, 2013). The control diets were corn-soybean meal-DDGS based and are typical of those used in the U.S. The NE content of the control diets ranged from 2,462 kcal/kg (grower 1) to 2,536 kcal/kg finisher 2-no RAC). The control diet with RAC was high energy (2,637 kcal/kg) with 4.0% added fat. The energy content of the LE diets decreased from 2,461 kcal/kg (grower 1) to 2,319 kcal/kg (finisher 2 with no RAC). This decrease in NE content was primarily created by increasing the percent wheat midds (5 to 20%) and soybean hulls (2 to 7.9%) from grower 1 to finisher 2 with no RAC. The LE finisher 2 diet with RAC contained 4% soybean hulls, 10% wheat midds and contained 2,385 kcal/kg of NE.

Individual BW and pen feed intake data were collected every 21 d corresponding with diet changes. The day prior to harvest, pigs were scanned ultrasonically using an Aloka 500v linear array ultrasound unit with a 3.5-MHz, 17-cm linear probe (Corometrics Medical Systems, Wallingford, CT) to obtain measurements of 10th rib backfat depth and longissimus muscle area. Pigs were transported to a commercial pork processor at the end of the experiment to collect hot carcass weight, and loin and backfat depth with an optical probe (Fat-O-Meter, Carometec, Herlev, Denmark). At the commercial pork processor. an approximate 5 cm x 5 cm sample was collected from the belly proximal to the midline split and below the teat line. The fat tissue samples were analyzed via NIR for fat iodine value (**IV**).

Statistical Analysis

Pen was used as the experimental unit (n = 40) for statistical analysis of all live animal and carcass measurements. Data were analyzed as a complete block design using the GLM procedure of SAS (SAS Inst. Inc., Cary, NC.). Growth and feed intake variables up to d 84 were evaluated for the effect of the dietary energy treatments. Growth and feed intake data from d 84 to 105, and overall growth and carcass data were analyzed as a factorial (2 x 2) of energy concentration and RAC treatments.

Results

The growth performance data for d 0 to 84 are presented in Table 3. Overall for the first 4 periods, the control pigs had 4.0% greater average daily gain (**ADG**) ($P < 0.001$), 2.2% greater gain:feed (**G:F**) ($P = 0.009$), 6.2% greater NE intakes ($P = 0.001$), but similar average daily feed intake (**ADFI**) (2.84 vs. 2.78 kg/d, $P = 0.14$) compared to pigs fed the LE diets. At the end of 84 d on test, pigs fed the control diets were 3.4 kg heaver (114.4 vs. 111.0 kg, $P = 0.001$) but had 1.96% poorer NE efficiency ($P = 0.047$) compared to pigs fed the LE diets.

The pig growth data for the last phase (d 84 to 105), overall data and carcass data are presented in Table 4. From d 84 to 105, pigs were assigned to the 2 x 2 factorial arrangement of dietary treatments (control or LE and 0 or 7.5 ppm RAC). For d 84 to 105, pigs fed the control and LE diets had similar ADG (1.016 vs. 1.019 kg/d; $P = 0.92$). However, pigs fed the LE diets had 5.9% greater ADFI (3.43 vs. 3.24 kg/d; $P = 0.008$) and tended to have lower NE intakes (8.06 vs. 8.38 Mcal/d; $P = 0.074$). Pigs fed the control diets had 6% greater G:F (0.315 vs. 0.296; $P = 0.027$). At the end of the trial, (d 105) pigs fed the control diets were 3.24 kg heavier than pig fed the LE diets (135.7 vs. 132.5 kg; $P = 0.015$).

In this final 21 d period, pigs fed RAC had 24.3% greater ADG (1.128 vs. 0.907 kg/d; $P = 0.0001$) and 22.8% greater G:F (0.337 vs. 0.274; $P = 0.0001$). The feeding of RAC had no impact on ADFI (3.35 vs. 3.32 kg/d; $P = 0.58$) but daily NE intakes were increased (8.40 vs. 8.04 Mcal/d; $P = 0.037$) in pigs fed RAC due to the added fat in the RAC diets. Pigs fed RAC were 4.65 kg heavier (136.5 vs. 131.8 kg; $P = 0.001$) than pigs fed diets without RAC. There were no significant dietary energy by RAC interactions ($P > 0.23$) for ADG, G:F, ADFI and final BW. For the entire feeding period (d 0 to 105), the pigs fed the control diets had 3.2% greater ADG (1.023 vs. 0.991 kg/d; $P = 0.014$) and 3.1% greater G:F (0.352 vs. 0.341; $P = 0.002$) with nearly identical ADFI (2.913 vs. 2.910 kg/d; $P = 0.94$).

During the final 21 d, the pigs fed control and LE diets had similar NE efficiency (0.1217 vs. 0.1258 kg/Mcal, respectively; $P = 0.20$; Table 5). Pigs fed RAC in Period 5 had 18.9 % greater NE efficiency than pigs not fed RAC (0.1345 vs. 0.1131 kg/Mcal, $P < 0.0001$). Over the entire 105 d feeding trial, pigs fed the LE diets had 1.95% greater NE efficiency than pigs fed the control diets (0.1437 vs. 0.1409 kg/Mcal, $P = 0.04$). Feeding RAC for the last 21 d improved the overall (d 0 to 105) NE efficiency by 5.0% (0.1457 vs. 0.1388 kg/Mcal, $P < 0.0001$). On a carcass weight gain basis, pigs fed the control vs. LE diets had similar overall NE efficiency (0.1065 vs. 0.1058 kg/Mcal, $P = 0.46$). Feeding RAC the last 21 d improved

overall (d 0 to 105) carcass gain NE efficiency by 6.9% (0.1097 vs. 0.1026 kg/Mcal, $P < 0.0001$).

Pigs fed the control diets had greater live ultrasound backfat depth (17.0 vs. 14.9 mm; $P = 0.005$) and loin eye area (50.8 vs. 48.9 cm^2; $P = 0.008$) than pigs fed the LE diets. Pigs fed RAC had 6.9% greater loin eye area (51.5 vs. 48.2 cm^2; $P = 0.0001$) than pigs fed diets without RAC with similar ultrasonic backfat (P=0.85). There were no significant dietary energy by RAC interactions (P =0.64) for ultrasound data.

Pigs fed the control diets had 4.54 kg greater carcass weight (102.69 vs. 98.15 kg; $P = 0.0001$) and 1.4% greater dressing percentage (75.63 vs. 74.23%; $P = 0.0001$) than pigs fed the LE diets (Table 4). Pigs fed the control diets had 1.46 mm greater optical probe fat depth ($P = 0.036$) and 3.14 mm greater LM depth ($P = 0.017$) than pigs fed the LE diets.

Pigs fed RAC had 4.89 kg greater carcass weight (102.87 vs. 97.98 kg; $P = 0.0001$) and 0.83% greater dressing percentage (75.35 vs. 74.52 %; $P = 0.0001$) than pigs fed diets without RAC. In agreement with the live ultrasound measurements, RAC did not affect carcass backfat depth (P= 0.67) and increased loin eye depth (60.15 vs. 56.57 mm; $P = 0.009$). Feeding RAC tended to increase predicted carcass percent lean (52.81 vs. 52.19 %; $P = 0.086$). Belly fat IV values were greater for pigs fed the LE diets (68.00 vs. 65.97, $P < 0.0001$) and pigs fed RAC (67.57 vs. 66.41; $P = 0.006$).

Discussion

As we increased the amount of wheat middlings and soybean hulls in the diets to decrease the NE of the diets, we observed a slight (4%) decline in growth rate and approximately 2% reduction in feed efficiency. The content of wheat middlings in our study increased from 5% to 20%. Cromwell et al. (1992) indicated that "heavy/starchy" wheat middlings could be included up to 20% without any effect on growth rate or feed efficiency and "light" wheat middlings could be included up to 10% without any impact on growth rate but would reduce feed efficiency by 4.5%. The quality of wheat middlings in our experiment may have been somewhere in between these two classifications as we did observe a slightly larger growth rate reduction, but less feed efficiency reduction than Cromwell et al. (1992) reported. More recently, Salyer et al. (2012) observed similar results to our findings in diets that also containing 15-30% DDGS, when wheat middlings were added at 10 or 20%, ADG and feed efficiency were reduced.

The soybean hulls increased in our diets from 2 to nearly 8% as the pig grew and dietary phases changed. This soybean hull inclusion would seem to be less of an issue in explaining our reduced growth rate based on the recent work by Goehring et al. (2012) where they did not observe any effect of soybean hulls at 7.5 or 15% of the diet on grow-finish pig growth rate, but did observe increased ADFI and poorer feed efficiency. However, earlier work by Bowers et al. (2000) reported that when soybean hulls increased to 6% or 9% in the finishing diets, pig ADG and feed efficiency were reduced by approximately 6%, which may suggest a similar variability in soybean hull quality as was reported for wheat middlings by Cromwell et al. (2000).

The effect of RAC to increase growth rate, feed efficiency, carcass weight and loin eye depth are similar to that of past research trials (Apple et al., 2007b; Schinckel et al., 2003b). What is interesting is that the use of RAC with the high by-product based diet sequence improved carcass weight to be equal to that of the pigs fed the control diets throughout the grow-finish period and may be a tool to be combined with high by-product feeding programs. Graham, et al. (2012) found that in 30% DDGS diets with 19% wheat midds, RAC improved carcass weights as well, but were still 0.82 kg lighter than the control-corn-SBM diets that did not have either the DDGS or wheat midds.

The energy concentration of the LE diets were decreased and fiber content increased to reduce energy intake of the high feed intake, high growth barrows, during the late finishing period to close to that needed for maximal protein accretion. In this study we may have decreased the NE too far or may have overestimated the amino acid availability of the by-product feedstuffs due to also reducing the loin muscle area and therefore protein mass and accretion. Cromwell et al. (2000) have document that there can be considerable variability in wheat middlings across the U.S. and the book values we used for wheat middlings and potentially soybean hulls may have been slightly inaccurate for sources used in this experiment. The responses to dietary fiber are affected by the types of fiber. Different types of fiber have different water holding capacity, rates of fermentation and impact on rates of passage, gut fill and visceral organ size (Kerr and Shurson, 2013; Lindberg, 2014). Repeating the trial with different feed ingredients with different types of dietary fiber would likely affect the results.

One of the objectives in this experiment was to decrease the ratio of lipid accretion to protein accretion in late finishing phases and attempt to increase the NE efficiency of BW gain. The ADG was reduced in the pigs fed the LE diets in approximate proportion to their decreased NE intakes. Overall, the LE pigs had 1.95% greater NE efficiency and had 1.46 mm less backfat depth than the control pigs. With increased carcass leanness, it is expected the gain:NE intake above main-

tenance should be greater for pigs fed the LE diet. For example, gilts which had 4.02 mm less backfat depth and 3.3% greater fat-free lean percentage (52.9 vs. 49.6% fat-free lean, Schinckel et al., 2012a,b) had approximately 13% greater gain:NE intake above maintenance. Based on the backfat differences between pigs fed the control and LE diets in this study, pigs fed the LE diets should have approximately 4.72% greater gain:NE intake above maintenance than pigs fed the control diets, yet only a 3% difference in gain:NE intake above maintenance was predicted. Most likely the maintenance requirements for energy are slightly greater for pigs fed the LE diets (Wenk, 2001). Feeding of LE diets with increased fiber concentrations can increase endogenous gut losses (Mariscal-Landin et al., 1995; Nyachoti et al., 1996). It is also possible that viscera organ mass increased with the feeding of the LE diets as this was reported for grow-finish pig diets with 30% soybean hulls and 30% wheat middlings by Stewart et al. (2013) and viscera mass has approximately 3 times greater maintenance requirement per $kg^{0.70}$ than muscle mass (Noblet et al., 1999).

In a recent large trial, pigs fed high energy, high fat diets (2.62 to 2.68 Mcal NE/kg, 8% fat and 11% NDF) had 1.3% greater NE efficiency (ADG:NE intake) than pigs fed similar low energy level diets as the current study (2.36 to 2.42 Mcal NE/kg, 3.8 to 4% fat and 15.3 to 15.5% NDF, Schinckel et al., 2012a,b). The increased fat percentage in the high energy diets in the previous trial vs. similar dietary fat percentages in the control and LE diets in this trial may partially explain the difference in the results. The high energy, high fat diets of the previous trial may have had an advantage in that the direct deposition of dietary fat to lipid accretion is an energetically efficient process (about 90%, Noblet and Milgen, 2004).

In the past trial (Schinckel et al, 2012a), the pigs fed the LE diets had greater ADFI and similar NE intakes (6.33 vs. 6.44 Mcal//d). In this trial the pigs fed the LE diets did not increase their ADFI to compensate for the decreased NE content of the LE diets. This was especially true for the late finishing phases which were fed in late July, August and early September. It is possible that the increased heat increment of the high fiber LE diets limited ADFI and ADG in the finishing phases (Coffey et al., 1982; Stahly and Cromwell, 1986).

Few trials have been published evaluating the impact of feeding high fiber diets on fatty acid profiles (Salyer et al., 2012). The use of by-products including DDGS, wheat midds and soybean hulls may increase the IV value of carcass fat. Pigs fed the LE diets may have decreased rates of de novo synthesis of fatty acids (Bee et al., 2002). Pigs with decreased energy intakes and are leaner; tend to have less saturated carcass fat (Asmus et al., 2014; Wood et al., 2008). In past research, the addition of 20% wheat midds to corn-soybean meal-DDGS (15%) diets increased jowl IV values by approximately 2.1 units (74.2 vs. 72.1) and backfat depth decreased (20.7 vs. 22.1 mm, Salyer et al., 2012). In Graham et al. (2012), the IV value of pigs fed corn-soybean meal based diets was compared to pigs fed diets containing corn, soybean meal plus 30% DDGS (12.3% oil) and 19% wheat midds. Pigs fed the high fiber diets (19.0% NDF vs. 9.2%) from 41 to 121 kg BW (90 d) had jowl IV values of 78.5 vs. 68.4 for pigs fed the corn soybean meal based diets. In the past, the IV value of carcass fat has been modeled as a linear function of the Iodine value product (**IVP**) of the diets fed. The effect of dietary fiber may be in addition to dietary differences in IVP. Past research has found carcass fat IV increases at or less than one unit when RAC is fed from 21 to 28 d (Apple et al., 2007a,b). Feeding of high levels of DDGS with other by-products and RAC may increase carcass fat IV values to the point of affecting fat quality (Graham et al., 2012; Xu et al., 2010). In this study higher fiber and RAC diets effects were additive in belly IV.

The LE diets using lower energy feed ingredients including wheat midds and soybean hulls resulted in diets that were lower cost per kg. The decreased ADG, dressing percentage, and carcass weight of the pigs fed the LE diets must be taken into account in estimation of the relative value of the low energy, high fiber feed ingredients to high energy ingredients including corn and fat. However, pork producers get paid on the basis of carcass weight. Feeding the lower cost LE diets reduced carcass weight gain and dressing percent. A further reduction of the fiber content of the final diet may increase dressing percentage and result in increased carcass weight gain (Amus et al., 2014; Xu et al., 2010a). The carcass weights of the pigs fed the LE diets and fed RAC was similar to that of the pigs fed the control diets and no RAC. The feeding of lower cost diets for most of grow-finish period and then feeding of RAC with diets with reduced fiber content is an alternative feeding strategy that should be researched in more depth.

Implications

The feeding of lower energy feed ingredient by-products results in reduced rates of BW and carcass weight gain, increased carcass leanness and slightly increased IV value of the carcass fat. If the changes in pig performance are taken into account, pork producers can estimate the relative value of the lower energy feed ingredients relative to carcass weights and revenue generated. Reduction of the fiber content of the last finishing diet and combined feeding of RAC should be evaluated to reduce the impact of the LE diets on carcass

weight gain and final IV values of the carcass fat tissues. Additional research is needed to estimate the impact of dietary fiber source and type on maintenance energy requirements.

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Table 1. Diet formulations for Control and Low NE grower diets (d 0-63).

	Control			Low NE		
Ingredient, %	**Grower 1**	**Grower 2**	**Grower 3**	**Grower 1**	**Grower 2**	**Grower 3**
Corn	50.125	60.222	66.520	43.795	48.907	49.390
SBM, 48% CP	23.400	15.250	9.850	21.800	12.220	6.950
DDGS - 7.5% fat	20.000	20.000	20.000	20.000	20.000	20.000
Soy hulls	0.000	0.000	0.000	2.000	4.000	5.000
Wheat midds	0.000	0.000	0.000	5.000	10.000	15.000
Swine grease	2.700	1.100	0.500	3.650	1.650	0.950
Limestone	1.610	1.470	1.400	1.630	1.470	1.390
Monocal. phos.	0.670	0.500	0.410	0.580	0.280	0.080
Vitamin premix	0.150	0.150	0.125	0.150	0.150	0.125
TM premix	0.150	0.150	0.130	0.150	0.150	0.130
Phytase	0.100	0.100	0.100	0.100	0.100	0.080
Salt	0.350	0.350	0.300	0.350	0.350	0.300
L-Lysine-HCL	0.400	0.400	0.420	0.430	0.420	0.400
DL-Methionine	0.080	0.040	0.020	0.090	0.040	0.000
L-Threonine	0.110	0.100	0.090	0.125	0.100	0.080
L-Tryptophan	0.030	0.030	0.035	0.025	0.025	0.025
CTC-50	0.100	0.100	0.000	0.100	0.100	0.000
Tylan 40	0.000	0.000	0.050	0.000	0.000	0.050
Rabon	0.025	0.038	0.050	0.025	0.038	0.050
Calculated Nutrients						
ME, kcal/kg	3413.8	3353.9	3338.8	3409.7	3286.4	3235.3
NE, Kcal/kg	2461.7	2452.1	2469.5	2461.5	2391.1	2366.3
SID lys,%	1.154	0.955	0.837	1.154	0.931	0.802
SID Lys/NE	**4.688**	**3.893**	**3.390**	**4.688**	**3.892**	**3.391**
Ca, %	0.84	0.730	0.670	0.840	0.710	0.640
Available. P, %	0.40	0.350	0.320	0.400	0.340	0.310

Table 2. Diet formulations for Control and Low NE finisher diets (d 63-105).

	Control			Low NE		
Ingredient, %	**Finisher 1**	**Finisher 2**	**Finisher 2 +RAC**	**Finisher 1**	**Finisher 2**	**Finisher 2 + RAC**
Corn	70.590	79.350	68.3925	49.280	55.225	63.7525
SBM, 48% CP	6.100	7.600	14.4300	5.000	5.000	9.4600
DDGS - 7.5% fat	20.000	10.000	10.0000	20.000	10.000	10.0000
Soy hulls	0.000	0.000	0.0000	6.000	7.900	4.0000
Wheat midds	0.000	0.000	0.0000	17.000	20.000	10.0000
Swine grease	0.500	0.500	4.0000	0.510	0.000	0.0000
Limestone	1.260	1.030	1.1200	1.160	0.960	1.1000
Monocal phos.	0.250	0.350	0.4500	0.000	0.000	0.1800
Vitamin premix	0.125	0.100	0.1500	0.125	0.100	0.1500
TM premix	0.130	0.100	0.1400	0.130	0.100	0.1400
Phytase	0.100	0.100	0.1000	0.050	0.050	0.0800
Salt	0.300	0.300	0.3000	0.300	0.300	0.3000
L-Lysine-HCL	0.420	0.350	0.3900	0.315	0.260	0.3800
DL-Methionine	0.010	0.030	0.1000	0.000	0.000	0.0600
L-Threonine	0.105	0.110	0.1600	0.045	0.050	0.1350
L-Tryptophan	0.035	0.030	0.0300	0.010	0.005	0.0250
Tylan 40	0.025	0.000	0.0000	0.025	0.000	0.0000
Rabon	0.050	0.050	0.0500	0.050	0.050	0.0500
Paylean, 4.0 g/kg	0.000	0.000	0.1875	0.000	0.000	0.1875
Calculated Nutrients						
ME, kcal/kg	3351.3	3366.4	3508.3	3203.9	3157.5	3237.2
NE, Kcal/kg	2503.5	2536.1	2636.9	2342.5	2318.6	2384.8
SID lys,%	0.744	0.701	0.894	0.697	0.642	0.808
SID Lys/NE	**2.970**	**2.764**	**3.390**	**2.976**	**2.769**	**3.390**
Ca, %	0.580	0.510	0.580	0.540	0.470	0.540
Available P, %	0.280	0.250	0.280	0.260	0.230	0.260

Table 3. Effect of dietary net energy level from d 0 to 84 on grow-finish pig growth performance.

	Control Diet Sequence	Low Energy Diet Sequence	SE	Diet P-Value
Number of pens:	20	20		
Number of pigs, d 0:	100	100		
Pre-ractopamine, d 0-84				
ADG, kg/d	1.024	0.983	0.0078	0.0009
ADFI, kg/d	2.836	2.783	0.0244	0.14
F:G	2.767	2.832	0.0161	0.008
G:F	0.362	0.354	0.0021	0.009

Table 4. Effect of dietary net energy level and ractopamine from d 84 to 105 on grow-finish pig growth performance and carcass values.

	Control Diet Sequence		Low Energy Diet Sequence			P-Value		
RAC, ppm:	**0**	**7.5**	**0**	**7.5**	**SE**	**Energy**	**RAC**	**E x RAC**
No. pens/pigs	10/50	10/50	10/50	10/50				
BW, d 84, kg	114.53	114.28	110.92	111.11	0.964	0.0016	0.97	0.82
Period 5, d 84-105								
ADG, kg/d	0.925	1.106	0.889	1.149	0.0320	0.92	0.0001	0.23
ADFI, kg/d	3.244	3.233	3.386	3.473	0.0668	0.008	0.57	0.46
F:G	3.517	2.938	3.844	3.033	0.0926	0.031	0.0001	0.22
G:F	0.286	0.343	0.262	0.330	0.0080	0.027	0.0001	0.47
BW, d 105, kg	133.96	137.50	129.59	135.39	1.251	0.015	0.0009	0.38
Overall, d 0-105								
ADG, kg/d	1.006	1.039	0.964	1.018	0.0119	0.014	0.001	0.36
ADFI, kg/d	2.951	2.875	2.907	2.913	0.0365	0.94	0.35	0.27
F:G	2.934	2.767	3.020	2.859	0.0256	0.0017	0.0001	0.90
G:F	0.341	0.362	0.332	0.350	0.0031	0.0016	0.0001	0.71
Carcass Data								
Hot weight, kg	100.62	104.76	95.33	100.97	1.078	0.0003	0.0001	0.49
Carcass yield, %	75.19	76.07	73.84	74.62	0.147	0.0001	0.0001	0.72
Carcass fat IV	65.01	66.93	67.81	68.20	0.390	0.0001	0.006	0.059

Table 5. Effect of dietary net energy level and ractopamine from d 84 to 105 on grow-finish pig net energy efficiency on a live weight and carcass basis (kg/Mcal).

	Control Diet Sequence		Low Energy Diet Sequence			P-Value		
RAC, ppm:	**0**	**7.5**	**0**	**7.5**	**SE**	**Energy**	**RAC**	**E x RAC**
Period 5, d 84-105	0.1131	0.1303	0.1131	0.1386	0.00321	0.20	0.0001	0.21
Overall, d 0-105	0.1374	0.1444	0.1402	0.1471	0.00127	0.04	0.0001	0.92
Carcass basis	0.1029	0.1102	0.1023	0.1092	0.00102	0.46	0.0001	0.88

Switching Feed Ingredients In/Out of Grow-Finish Diets

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Summary

The use of by-product feed ingredients is ever increasing in the swine industry today as we continually strive to make the most cost effective nutrition program with minimal impacts on pig performance. We tested a practical approach of feeding four common by-product feed ingredients, corn distillers dried grains with solubles, wheat middlings, soybean hulls, and bakery meal at either a constant blending of each in the diet at 3.75% or individually, abruptly, and randomly alternating each ingredient into the diet at 15% for a 14-day period. For the overall grow-finish period (112 days), there was no effect on growth performance or carcass composition due to either method of by-product feeding. However, wheat middlings was associated with reduced daily gains in both 14-day periods it was fed. Soybean hulls tended to reduce feed intakes and bakery meal tended to increase feed intake, especially when it followed soybean hulls in the diet at 15%. There appears to be by-product feeding sequences that may reduce performance and others that may provide a stimulation or compensation in growth performance. More research with by-products, inclusion rates, and sequences is needed to provide nutritionists and producers with a better understanding of how and when to utilize these by-product feedstuffs in their nutrition program.

Introduction

Abruptly switching or changing major dietary feedstuffs in and out of swine diets has traditionally not been recommended as it may compromise growth. Patience (2010) provided the standard industry recommendation when he suggested that we need to make ingredient changes "conservatively and gradually" especially when the quantities of alternative products are greater than 15% of the diet. In the past few years, dietary programs in grow-finish production are being changed more frequently because of the economics of production and the varied availability of alternative products. With price and (or) supply volatility, producers are 'wanting to' or 'having to' switch ingredients in and out of their formulations, quickly and unpredictably, to successfully control costs and derive the greatest income given the set of circumstances.

Little has been written in research archives about the abrupt and random switching of dietary ingredients in and out of a multi-phase grow-finish feeding program. In most of the contemporary by-product feeding research, by-products have been added and fed continuously, while some have been added in incrementally increasing amounts (Goehring et al., 2012; Paulk et al., 2012; Salyer et al., 2012). Two recent studies have considered the effects of switching alternative ingredients in and out of the finishing diet sequence. Potter et al. (2010) conducted a 6-week study in early finishing (20 to 53 kg) assessing bi-weekly, abrupt switching of two different diet formulation approaches; either formulating the diet using primarily corn and soybean meal or formulating the diet using corn, soybean meal, corn hominy and distillers dried grains with solubles (**DDGS**). Improvements in average daily feed intake (**ADFI**) and average daily gain (**ADG**) favoring the by-product based formulation were observed in the second 2-week period, even though the same formulation (although maybe different lots of ingredients) was fed in the first 2-week period. Likewise, in the third 2-week period, an inexplicable tendency towards improved ADFI and ADG were observed with the feeding of the corn-soybean meal control formulation. However, nothing could be deducted about the impact of which direction the switch was made.

More recently, Hilbrands et al. (2013) studied the effects of abrupt addition and removal of good and poor quality DDGS from the grow-finish feeding program on growth performance and carcass characteristics. Hilbrands et al. (2013) evaluated swapping in and out 20 or

40% DDGS and 40% DDGS of either high or low standardized ileal digestible (**SID**) lysine quality. Abruptly switching to 40% DDGS reduced pig ADFI, ADG and gain:feed (**G:F**) at different time points of the grow-finish period. When pigs were switched to 40% of either SID lysine DDGS short term, feed intake (day 3 or 7 post-switch) was reduced by between 150-400 g/d. The opposite was true when pigs were switched from the 40% DDGS to a corn-soybean meal diet, in that short term feed intake went up by approximately 200-300 g/d. Overall, both research groups reported that there were few long term detrimental effects on growth performance due to switching these three corn by-products in and out of the grow-finish swine feeding program.

Due to the lack of previous research in by-product ingredient use, sequencing, and random abrupt switching of these by-products in and out of the feeding program, the following experiment was conducted to evaluate randomly and abruptly switching four common alternative feed ingredients in and out of the diet on growth performance and carcass characteristics of grow-finish pigs.

Materials and Methods

A total of 417 crossbred pigs were assigned by body weight (27.6 ± 0.78 kg) to one of three dietary treatments. Dietary treatments were:

1. Control—corn-soybean meal based diet
2. Switch—a by-product feed ingredient was included at 15% of the diet for 2 weeks and then another by-product was fed the next 2 weeks, etc.
3. Blend—all four by-products used as switching ingredients were included at 3.75% of the diet all the time.

Three stations provided data for the project and followed the same protocol for diet formulations and by-product switching order. The participating stations and the number of replications contributed to the study were: Michigan State University (four pens/treatment with 14 pigs/pen), Purdue University (four pens/treatment with five pigs/pen), and University of Minnesota (seven pens/treatment with nine pigs/pen). All pens were of mixed sex with equal sex ratios in each pen within stations. Pigs were housed between 0.65-0.84 m^2/pig (depending on station) and pens were over totally slatted concrete floors with ad libitum access to a self-feeder and waterer. Each pen had a minimum of one feeder hole and one drinker per eight pigs.

Pigs and feeders were weighed initially and every 14 days until completion of the 16-week study. The third day after the dietary switch, all feeders were weighed to obtain a 3-day feed intake post-dietary switch (data not presented). Pens with pigs that were fed the switching diets had their feeders emptied prior to making the switch to the next by-product diet. The day prior to harvest, pigs were scanned ultrasonically using an Aloka 500v linear array ultrasound unit with a 3.5-MHz, 17-cm linear probe (Corometrics Medical Systems, Wallingford, CT) to obtain measurements of tenth rib backfat depth and loin eye area. Pigs from Purdue University were also transported to a commercial pork processor at the end of the experiment to collect hot carcass weight, and loin and backfat depth with an optical probe (Fat-O-Meter, Carometec, Herlev, Denmark).

There were eight 14-d dietary phases (two 14-d periods per the four nutrient phases of Grower 1, 2, and Finisher 1, 2). The diets were formulated to meet the nutrient needs for medium lean gain genetics for each phase using nutrient levels and ingredient nutrient values for content and digestibility from the National Swine Nutrition Guide (2010). Diets were formulated to be equal in SID lysine and ME content by adjusting the corn, choice white grease (or soy oil), and synthetic amino acids in the diets (Tables 1-4). The by-product feed ingredients chosen for this study were: bakery meal, corn DDGS, soybean hulls, and wheat middlings. Alternative feed ingredients used in the experiment were multi-lots from a single source within station. Antibiotics were added to all diets according to normal operating procedures at each station and balanced by changing levels of corn in the diets.

The by-product ingredient sequences at 15% of the diet were predetermined as a random order by the research committee and were:

Weeks 0-2	Wheat middlings
Weeks 2-4	DDGS
Weeks 4-6	Bakery meal
Weeks 6-8	Soybean hulls
Weeks 8-10	Bakery meal
Weeks 10-12	DDGS
Weeks 12-14	Soybean hulls
Weeks 14-16	Wheat middlings

Statistical Analysis

Pen was used as the experimental unit (n = 45) for statistical analysis of all live animal and carcass measurements. Data were analyzed as a randomized design with diet, station, and diet by station interaction included in the model using the GLM procedure of SAS (SAS Inst. Inc., Cary, NC.). Data were further tested for diet effects using the Duncan's mean separation tests at $P < 0.05$ for significance and $0.05 < P \leq 0.10$ for trends.

Results

The station effect was significant for most of the response variables. However, there were very few station by dietary treatment interactions (Table 5) and, therefore, they will not be discussed in detail in this paper.

During Period 1 (days 0-14), there was no effect of the blended by-product based diet or feeding the 15% wheat middlings on ADFI or G:F compared to the control diet (Table 5). However, feeding 15% wheat middlings did decrease ADG by 5.4% compared to the control fed pigs ($P < 0.05$).

During Periods 2 (days 14-28) and Period 3 (days 28-42), feeding a blend of by-products or 15% DDGS during Period 2 or 15% bakery meal during Period 3 had no effect on ADG, ADFI, or G:F ($P > 0.20$).

During Period 4 (days 42-56), the switch dietary treatment changed to 15% soybean hulls and resulted in reduced ADFI ($P<0.05$) compared to both the control and blended by-product treatments. However, there was no effect of dietary treatment on ADG, which lead to the pigs on the switch soybean hulls diet tending to have better G:F ($P < 0.10$) than the control and blended by-product treatments.

During Period 5 (days 56-70), the pigs fed the switch diet sequences were fed 15% bakery meal which resulted in increased ADFI ($P < 0.05$) over the blended by-product treatment with the control pigs being intermediate and not different from the other treatments. There was no effect of dietary treatment on ADG, but pigs fed the blended by-product diet tended to have better G:F ($P < 0.10$) than both the control and switch treatments during this feeding period.

From days 70-84 (Period 6), the switching by-product diet sequence pigs were fed 15% DDGS and had reduced ADFI and ADG compared to the control fed pigs ($P < 0.05$). Also, the blended by-product treatment tended ($P < 0.10$) to be lower in both ADG and ADFI than the control treatment. There were no differences in G:F among treatments during this time period.

During period 7 (days 84-98), there were no effects of dietary treatments on ADG or ADFI. Pigs fed soybean hulls in the switch diet did tend to have improved G:F ($P < 0.10$) compared to the control and blended treatments due to a numerical reduction in ADFI and numerical improvement in ADG in Period 7.

During Period 8 (days 98-112), feeding 15% wheat middlings in the switching diet sequence reduced ADG ($P < 0.05$) compared to both the control and blended dietary treatments and G:F was reduced ($P < 0.05$) compared to the blended treatment, with the control fed pigs being intermediate in feed efficiency.

Overall (days 0-112), there was no effect of either blending the by-products at a constant 3.75% level or continually switching them in and out of the diet at 15% inclusion on ADG, ADFI, or G:F for the entire grow-finish period. This resulted in statistically similar final body weights, tenth rib loin eye areas, and tenth rib backfat thickness at the end of the study.

Discussion

The use of by-product feed ingredients is ever increasing in the swine industry today as we continually strive to make use of these alternatives in the most cost effective nutrition program. It has been commonly thought for some time by many swine nutritionists that, when using alternative ingredients, there is a need to acclimate the pig to the new ingredients (Patience, 2010). However, in today's dynamic world of low cost alternative ingredients that are suddenly available, and feed mill limitations on the number of ingredients that can be stored, we may need to pulse in higher inclusion rates of these by-products with no adjustment period due to underlying costs, economics, and mill space limitations.

Recently, Salyer et al. (2012) observed when adding wheat middlings at 10 or 20%, in diets that also contained 15-30% DDGS, ADG and G:F were reduced. In our study, we did not already have DDGS in the diet, but we too observed that 15% wheat middlings in diets during both 14-day periods reduced ADG and G:F in the finishing period of feeding wheat middlings. This partially agrees with Cromwell et al. (1992) who indicated that "heavy/starchy" wheat middlings could be included up to 20% without any effect on growth rate or feed efficiency and "light" wheat middlings could be included up to 10% without any impact on growth rate but would reduce feed efficiency by 4.5%. The quality of wheat middlings across all three stations in our experiment may have been somewhere in between these two classifications as we did observe a slightly larger growth rate reduction compared to Cromwell et al. (1992) and only the reduction in feed efficiency occurred during the last period before slaughter.

The recent work by Goehring et al. (2012) did not observe any effect of soybean hulls at 7.5 or 15% of the diet on grow-finish pig growth rate, but did observe increased ADFI and poorer feed efficiency. We found slightly different results when feeding 15% soybean hulls for 14-day periods. We observed a significant reduction in ADFI during the grower period and numerical reduction in ADFI during the finisher period but improved feed efficiency in both periods. This may have to do more with the random sequence that soybean hulls followed bakery meal in the grower period and DDGS

in the finisher period. The palatability of soybean hulls maybe substantially less than bakery meal, but not as different from DDGS.

Paulk et al. (2012) reported that feeding 7.5 and 15% bakery meal linearly reduced feed efficiency for the entire grow-finish period with no effect on ADG and only a numerical increase in ADFI. In our study during the grower pig phase, there was only a numerical increase in ADFI and ADG with no difference in G:F when the bakery meal followed DDGS. However, when the bakery meal followed soybean hulls, ADFI was significantly increased with again a numerical increase in gain which lead to similar G:F to the control pigs and poorer G:F than the blended treatment in the finisher phase.

Corn DDGS has been reported by multiple investigators to have minimal impact on pig performance or the carcass when included at 20-30% or less in the diet (Stein and Shurson, 2009; Xu et al., 2010). The 15% DDGS diet did not significantly impact the grower period performance, but did decrease ADG and ADFI in the finisher period. This may be related to a sequencing effect because in the grower period, DDGS followed wheat midds but in the finisher period, DDGS followed bakery meal. So the palatability of DDGS may be more similar to wheat middlings than bakery meal and may change the pig's intake and resultant gain during short periods of time (e.g., 14-day periods in this study).

This study only tested one specific random sequence of feed ingredients in the switching treatment. It is clear that there is a relationship of the prior diet composition/ingredients on the next period feed intake. Comparing the switching diet to the blended by-product or control treatment as pigs switched to bakery meal in periods 3 and 5, the change in ADFI between periods increased by 0.1-0.28 kg/d more with bakery meal than the control or blended treatments between periods. When we look at soybean hulls following the bakery meal, ADFI only increased by 0.16 kg/d for the soybean hull fed pigs but control pigs increased 0.4 kg/d in the same period. The same thing happened when DDGS followed bakery meal in Period 6; pigs fed DDGS actually had a decrease in ADFI (-0.19 kg/d) while the control and blend treatments increased slightly (0.01 and 0.03 kg/d). This has only been reported one other time in the literature. Hilbrands et al. (2013) reported that abruptly switching to 40% of a high quality DDGS decreased ADFI, and during the grower period this abrupt switching also decreased ADG and G:F. In their second study, they also measured the short term effects of a high or low quality DDGS and the switching to the low quality DDGS could reduce ADFI in the short term by as much as 400 g/d, while switching from the low or high quality DDGS to a corn-soybean meal diet would actually increase short-term ADFI by approximately 200-300 g/d. Part of the short-term change may be related to the pig's preference for feed ingredients. Pigs do have preferences for different cereal grains, protein, and fiber ingredients and this may be related to the starch or fiber content of the ingredients, its texture, and their digestibility (Sola-Oriol et al., 2009ab, 2011, 2014).

There were a few station by treatment interactions for Period 6 and 7 ADFI; one station had a slight increase in ADFI and the other two stations had slight decreases in ADFI due to the switching to DDGS or soybean hulls. This may indicate a variation in by-product qualities across the Midwest as each station was responsible for sourcing their own by-products. Cromwell et al. (2000) have documented that there can be considerable variability in wheat middlings across the U.S. and the same may be true for the other three by-products sources used in this experiment.

Implications

The feeding of by-product feed ingredients may result in reduced (or increased) rates of ADFI and ADG in short term feeding periods as tested here, depending on the ingredient. However, long term adaptation to these by-products was not evaluated in this study and may change the use dynamics of any of these ingredients and their impact on pig performance. Nutritionists and pork producers need to estimate the relative value of the by-product feed ingredients relative to target carcass weights and revenue for that barn or system before implementing their level of use. For the overall grow-finish period (112 days), there was no effect on growth performance or carcass composition due to either method of constant blending (3.75%) or 15% pulsing of these by-products. However, it is clear that all these by-products may have a short term impact (positive or negative) on some parameter of pig performance. There appears to be by-product feeding sequences that may reduce performance and others that may provide a stimulation or compensation in growth performance. Repeating the experiment with different feed ingredients with different types of dietary fiber, energy, or nutrient profiles would likely affect the results of the study.

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Table 1. Grower 1 diet formulations for by-product switching study (days 0-28).[1]

Ingredient, %	Control	By-Product Blend	Weeks 0-2 Wheat Midds	Weeks 2-4 DDGS
Corn	71.370	55.720	55.490	56.810
Soybean meal	24.750	24.750	24.750	24.750
Choice white grease or soy oil	1.000	1.900	2.200	0.930
Limestone	1.050	1.080	1.210	1.240
Dicalcium phosphate	0.660	0.480	0.310	0.290
Vitamin premix	0.150	0.150	0.150	0.150
Trace mineral premix	0.100	0.100	0.100	0.100
Selenium premix	0.050	0.050	0.050	0.050
Phytase premix	0.100	0.100	0.100	0.100
Salt	0.300	0.300	0.300	0.300
Soybean hulls	0.000	3.750	0.000	0.000
DDGS	0.000	3.750	0.000	15.000
Wheat middlings	0.000	3.750	15.000	0.000
Bakery meal	0.000	3.750	0.000	0.000
Lysine-HCl	0.300	0.250	0.230	0.230
DL-methionine	0.050	0.030	0.020	0.000
L-threonine	0.070	0.040	0.040	0.000
Antibiotic	0.050	0.050	0.050	0.050
Total	100.000	100.000	100.000	100.000
Calculated Composition				
ME, kcal/kg	3,383.70	3,383.50	3,383.90	3,383.80
Crude protein, %	18.05	19.15	19.01	20.80
Lysine, %	1.17	1.18	1.16	1.19
SID lysine, %	1.00	1.00	1.00	1.00
Calcium, %	0.65	0.65	0.65	0.65
Phosphorus, %	0.49	0.49	0.52	0.49
Available phosphorus, %	0.28	0.28	0.28	0.28

[1] Composition of corn, soybean meal, and by-product ingredients based on composition given in the National Swine Nutrition Guide (2010).

Table 2. Grower 2 diet formulations for by-product switching study (days 28-56).[1]

Ingredient	Control	By-Product Blend	Weeks 4-6 Bakery	Weeks 6-8 Soy Hulls
Corn	75.450	59.780	61.970	57.200
Soybean meal	20.700	20.700	20.700	20.700
Choice white grease or soy oil	1.170	2.070	0.000	4.610
Limestone	1.050	1.080	1.000	0.860
Dicalcium phosphate	0.490	0.310	0.500	0.500
Vitamin premix	0.150	0.150	0.150	0.150
Trace mineral premix	0.100	0.100	0.100	0.100
Selenium premix	0.050	0.050	0.050	0.050
Phytase premix	0.100	0.100	0.100	0.100
Salt	0.300	0.300	0.000	0.300
Soybean hulls	0.000	3.750	0.000	15.000
DDGS	0.000	3.750	0.000	0.000
Wheat middlings	0.000	3.750	0.000	0.000
Bakery meal	0.000	3.750	15.000	0.000
Lysine-HCl	0.300	0.260	0.300	0.260
DL-methionine	0.030	0.010	0.020	0.055
L-threonine	0.060	0.040	0.060	0.065
Antibiotic	0.050	0.050	0.050	0.050
Total	100.000	100.000	100.000	100.000
Calculated Composition				
ME, kcal/kg	3398.50	3398.50	3398.80	3398.70
Crude protein, %	16.44	17.56	16.94	16.71
Lysine, %	1.06	1.07	1.06	1.09
SID lysine, %	0.90	0.90	0.90	0.90
Calcium, %	0.60	0.60	0.60	0.60
Phosphorus, %	0.45	0.44	0.45	0.42
Available phosphorus, %	0.24	0.24	0.24	0.24

[1] Composition of corn, soybean meal, and by-product ingredients based on composition given in the National Swine Nutrition Guide (2010).

Table 3. Finisher 1 diet formulations for by-product switching study (days 56-84).[1]

Ingredient, %	Control	By-Product Blend	Weeks 8-10 Bakery	Weeks 10-12 DDGS
Corn	81.785	66.095	67.770	67.150
Soybean meal	14.720	14.720	14.720	14.720
Choice white grease or soy oil	1.000	1.910	0.060	0.930
Limestone	1.040	1.080	1.000	1.220
Dicalcium phosphate	0.340	0.160	0.350	0.000
Vitamin premix	0.150	0.150	0.150	0.150
Trace mineral premix	0.100	0.100	0.100	0.100
Selenium premix	0.050	0.050	0.050	0.050
Phytase premix	0.100	0.100	0.100	0.100
Salt	0.300	0.300	0.300	0.300
Soybean hulls	0.000	3.750	0.000	0.000
DDGS	0.000	3.750	0.000	15.000
Wheat middlings	0.000	3.750	0.000	0.000
Bakery meal	0.000	3.750	15.000	0.000
Lysine-HCl	0.300	0.255	0.295	0.230
DL-methionine	0.010	0.000	0.000	0.000
L-threonine	0.055	0.030	0.055	0.000
Antibiotic	0.050	0.050	0.050	0.050
Total	100.000	100.000	100.000	100.000
Calculated Composition				
ME, kcal/kg	3398.40	3398.60	3398.50	3398.20
Crude protein, %	14.11	15.22	14.56	16.90
Lysine, %	0.89	0.90	0.89	0.92
SID lysine, %	0.75	0.75	0.75	0.75
Calcium, %	0.55	0.55	0.55	0.55
Phosphorus, %	0.39	0.39	0.39	0.39
Available phosphorus, %	0.20	0.20	0.20	0.21

[1] Composition of corn, soybean meal, and by-product ingredients based on composition given in the National Swine Nutrition Guide (2010).

Table 4. Finisher 2 diet formulations for by-product switching study (days 84-112).[1]

Ingredient, %	Control	By-Product Blend	Weeks 12-14 Soy Hulls	Weeks 14-16 Wheat Midds
Corn	87.395	71.705	69.140	71.430
Soybean meal	9.450	9.450	9.450	9.450
Choice white grease or soy oil	1.000	1.900	4.460	2.240
Limestone	0.950	0.990	0.770	1.120
Dicalcium phosphate	0.350	0.170	0.360	0.000
Vitamin premix	0.100	0.100	0.100	0.100
Trace mineral premix	0.050	0.050	0.050	0.050
Selenium premix	0.025	0.025	0.025	0.025
Phytase premix	0.100	0.100	0.100	0.100
Salt	0.250	0.250	0.250	0.250
Soybean hulls	0.000	3.750	15.000	0.000
DDGS	0.000	3.750	0.000	0.000
Wheat middlings	0.000	3.750	0.000	15.000
Bakery meal	0.000	3.750	0.000	0.000
Lysine-HCl	0.270	0.225	0.230	0.200
L-threonine	0.035	0.010	0.040	0.010
Antibiotic	0.025	0.025	0.025	0.025
Total	100.000	100.000	100.000	100.000
Calculated Composition				
ME, kcal/kg	3409.70	3409.60	3409.90	3411.90
Crude protein, %	12.03	13.14	12.28	13.00
Lysine, %	0.73	0.74	0.75	0.71
SID lysine, %	0.60	0.60	0.60	0.60
Calcium, %	0.50	0.50	0.50	0.50
Phosphorus, %	0.37	0.37	0.35	0.40
Available phosphorus, %	0.19	0.19	0.19	0.19

[1] Composition of corn, soybean meal, and by-product ingredients based on composition given in the National Swine Nutrition Guide (2010).

Table 5. Effect of switching by-product feedstuffs in the diet every 14 days compared to a constant blend or a control diet on grow-finish pig growth performance.

	Control	Blend	Switch	SE	Diet *P*<
BW, day 0, kg	26.7	26.8	26.7	0.78	0.99
BW, day 112, kg[1]	128.0	125.9	125.4	1.99	0.62
Period 1 (days 0-14)			**Wheat Middlings**		
ADFI, kg	1.61	1.58	1.53	0.035	0.35
ADG, g	781[a]	769[ab]	739[b]	14.9	0.13
G:F	0.488	0.487	0.483	0.0057	0.78
Period 2 (days 14-28)			**DDGS**		
ADFI, kg	2.01	1.98	1.95	0.037	0.55
ADG, g	900	874	871	12.3	0.20
G:F	0.447	0.441	0.446	0.0064	0.76
Period 3 (days 28-42)			**Bakery Meal**		
ADFI, kg	2.22	2.22	2.29	0.053	0.54
ADG, g	872	871	899	14.2	0.29
G:F	0.397	0.393	0.395	0.0089	0.95
Period 4 (days 42-56)			**Soy Hulls**		
ADFI, kg	2.62[a]	2.56[a]	2.45[b]	0.046	0.04
ADG, g	1003	998	996	17.6	0.96
G:F	0.384[y]	0.391[y]	0.409[x]	0.0069	0.03
Period 5 (days 56-70)			**Bakery Meal**		
ADFI, kg	3.08[ab]	2.96[a]	3.13[b]	0.044	0.03
ADG, g[3]	1009	1013	1014	17.1	0.98
G:F	0.329[x]	0.342[y]	0.324[x]	0.0048	0.03
Period 6 (days 70-84)			**DDGS**		
ADFI, kg[3]	3.09[ax]	2.99[aby]	2.94[by]	0.039	0.03
ADG, g[3]	1003[ax]	964[aby]	957[by]	15.9	0.10
G:F	0.325	0.323	0.328	0.0045	0.76
Period 7 (days 84-98)			**Soy Hulls**		
ADFI, kg[3]	3.21	3.18	3.09	0.056	0.30
ADG, g	873	874	915	24.0	0.37
G:F	0.274[x]	0.275[x]	0.295[y]	0.0073	0.09
Period 8 (days 98-112)[1]			**Wheat Middlings**		
ADFI, kg	3.22	3.09	3.13	0.067	0.35
ADG, g	832[a]	824[a]	736[b]	27.9	0.04
G:F	0.260[ab]	0.270[a]	0.241[b]	0.0086	0.06
Overall (days 0-112)					
ADFI, kg	2.61	2.56	2.55	0.032	0.38
ADG, g	910	908	901	8.2	0.70
G:F[3]	0.349	0.356	0.354	0.0028	0.23
Ultrasound preslaughter, 10th rib					
Loin eye area, cm[2]	48.8	48.1	48.4	0.58	0.22
Backfat, mm	21.3	20.2	20.4	0.47	0.69

[a,b] Means with different superscript letters differ ($P < 0.05$) based on Duncan's means separation test.

[x,y] Means with different superscript letters differ ($P < 0.10$) based on Duncan's means separation test.

[1] Michigan State University data omitted due to topping out pens (8 of 14 pigs) on day 98. Data represent 11 pens per treatment.

[3] Diet by station interaction ($P < 0.05$).

A Multidisciplinary, Multi-Site Study of Feed Efficiency in Swine: What Have We Learned?

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Summary

We are reporting a 5-yr project that is entitled "Enhancing sustainability and competitiveness of the U.S. pork industry by improving nutrient utilization and feed efficiency through innovative scientific and extension approaches." This project takes advantage of one of the Iowa State University genetic swine herds, which has been selected for reduced Residual Feed Intake (RFI) for what is now 10 generations. One of the key objectives of this project was to determine if pigs highly selected for improved feed efficiency over multiple generations could withstand nutritional, immunological, physiological, and behavioral stresses, comparable to pigs that had not been so selected. This review will discuss some of the findings on genetic selection, growth performance, carcass composition and meat quality, protein turnover, behavior, and immunological stress. We are already able to report that pigs divergently selected for feed efficiency based on RFI can withstand these stresses, comparable to pigs that had not been so selected.

Introduction

U.S. pork producers sold 116.4 million head of market hogs in 2013 based on a national inventory of 65.2 million head (USDA, 2014). This represents total production of 11.6 million tonnes on a carcass weight basis. One can estimate that the total quantity of feed required by the U.S. pork industry exceeds 45 million tonnes annually, at a cost of about $12 billion. Significantly, in the production of pork, feed is the largest single expense, representing 55 to 60% of the total.

In this context, feed efficiency is an important driver of profitability. Each point of improvement in whole herd feed conversion (e.g., 2.90 to 2.89) represents about 1.6 kg of feed per pig or 186 million tonnes per year for the industry as a whole, and at a cost savings of about $0.40 per pig. Obviously, these economic values can vary widely among years, as feed costs fluctuate, but there is no argument that improvements in feed conversion, when achieved through economical means, represent a significant contributor to profitability in the pork industry.

What do we mean by "achieved through economical means?" Nutritionists understand that in some respects, feed conversion can be an almost "dial up" outcome. If an improvement in feed efficiency is desired, a higher energy diet can be fed; however, the new diet with a better feed efficiency may not be more profitable (Gutierrez et al., 2012). Therefore, in any conversation on feed conversion, practical and economic considerations are foremost.

Feed conversion is closely related to dietary energy concentration under well-controlled conditions. Increasing dietary energy in a given herd will almost always result in an improvement in feed efficiency (Beaulieu et al., 2009). However, more broadly, the correlation between energy in the diet and feed conversion - expressed on a live or carcass weight basis - can be shockingly small (Oresanya et al., 2008). Therefore, feed efficiency is not a simple topic in either scientific or production terms.

NIFA Feed Efficiency Project

The 5-yr project on which we are reporting is entitled "Enhancing sustainability and competitiveness of the U.S. pork industry by improving nutrient utilization and feed efficiency through innovative scientific and extension approaches." The project integrates both research and extension methods, with the research component taking advantage of the Iowa State University swine genetic herd, which has been selected for reduced Residual Feed Intake (**RFI**) for what is now 10 generations. RFI will be explained in greater detail below. The specific objectives of the project are:

1. Quantify the performance of pigs selected for increased feed efficiency under corn-soybean diets when fed lower quality by-product ingredients (higher fiber, lower fat).
2. Evaluate the ability of pigs selected for increased feed efficiency to cope with behavioral, physiological and immunological stressors.

3. Develop industry-ready tools to easily and effectively identify and select more efficient pigs.
4. Increase pork producers' awareness of the factors influencing feed efficiency and strategies available to achieve improvement.
5. Ensure the rapid and effective implementation of new technologies to improve feed efficiency both nationally and internationally.

The rationale behind the research objectives is that a comprehensive understanding of this unique population of pigs with lines that are divergently selected for feed efficiency based on RFI will increase our understanding of feed efficiency, and will hopefully identify new technologies and improved management procedures that can be applied more broadly by the U.S. pork industry. In other words, these selection lines are a model to study and comprehensively understand feed efficiency gains in swine. The most exciting aspect of the project is the multi-disciplinary approach that integrates swine genomics, quantitative genetics, proteomics, nutrition, immunology, meat science, bioinformatics, statistics, microbiology, physiology, and behavior into a single project. This not only enhances the potential for scientific advancement, but also provides unique undergraduate and graduate training opportunities. The scientists involved in this project are listed in Table 1.

Residual Feed Intake—Genetic Selection Lines

Over several years, the evaluation of feed efficiency has been measured as either the gain to feed ratio or the feed to gain ratio. In 1963, Koch et al. adjusted feed consumed for gain and mid-weight in order to evaluate what they called residual feed intake (RFI). Animals with lower RFI are more efficient and animals with high RFI are less efficient. RFI is calculated (Figure 1) as the difference between observed feed intake and expected feed intake, taking into consideration the animal's rate of gain and body weight back fat content (Koch et al., 1963; Kennedy et al., 1993).

At Iowa State University, two lines of pigs have been developed to demonstrate and study the biological and physiological differences between lines that were divergently selected for high versus low RFI (Young and Dekkers, 2012). The study was initiated in 2001, using purebred Yorkshire pigs within two populations: a line selected for decreased (low) RFI and a line that was initially randomly selected. In generation 5, selection for increased RFI was initiated in the randomly selected line, which was then referred to as high RFI. During each generation, boars and gilts selected on estimated breeding value up to that point were used to produce the next generation of pigs. After 8 generations of selection, RFI was found to be moderately heritable (0.29 + 0.07) and responded well to selection. As a result of RFI selection, body composition, physiological activity, maintenance requirements, digestibility, energetic efficiency, tissue turnover rates, and immune response are among the many factors that might be affected in RFI lines and will be discussed through this review.

Over 8 generations of selection, RFI was reduced by 241 g/d, average daily feed intake (**ADFI**) was reduced by 376 g/d and feed conversion was improved by 0.22 kg/kg. Back fat was reduced by 2.5 mm and interestingly; loin eye area increased by 1.5 mm. Average daily gain (**ADG**) was reduced by 79 g/d (Figure 2).

One of the key objectives of this project was to determine if pigs highly selected for improved feed efficiency over multiple generations could withstand nutritional, immunological and behavioral stresses comparable to pigs that had not been so selected. Concern is sometimes expressed that animals selected for increased efficiency are more susceptible to disease and "stress"and produce meat of inferior eating quality.

Growth Performance

To determine if the low RFI pigs (**LRFI**) would maintain their differences over the high RFI pigs (**HRFI**) when fed a less energy dense diet, an experiment was undertaken to compare diets of widely varying energy content. The logic was that diet energy concentration may vary widely in the future as higher energy ingredients such as corn, soybean meal, and fat become more expensive, and less expensive alternatives often contain much less energy and more fiber. The control diet used in this study, reflecting the diet used for the multi-generational selection program, was a typical corn-soybean meal diet, containing 3.32 Mcal ME/kg and 2.47 Mcal NE/kg. The experimental diets, which also contained 20% soyhulls, 20% wheat middlings and 7% corn bran, were formulated to contain 2.87 Mcal ME/kg and 2.03 Mcal NE/kg. In other words, dietary energy concentration was reduced by about 18%. All diets were formulated to contain equal quantities of calcium and available phosphorus. Diets did not contain a constant lysine:NE ratio, as we were concerned that such a drop in amino acid content could result in confounding of the results. However, a constant lysine content was also considered problematic. Therefore, middle ground was selected; retrospective analysis of the outcomes confirmed that amino acid intake was not limiting pig performance on either dietary regime.

Three generations of grow-finisher pigs have been evaluated in this experiment. In only one of the three generations was ADG reduced in the LRFI compared to the HRFI pigs when fed the control diet; otherwise, ADG was similar in both lines. The profile of ADG was similar on the low energy diets; only in one generation was ADG reduced in the LRFI pigs compared to the HRFI pigs. As expected, feed intake was lower, or tended to be lower, in the LRFI pigs fed either diet.

Thus, improved feed efficiency was observed in the LRFI pigs compared to the HRFI pigs in all three generations on the high energy diet. This advantage, however, was completely lost when the pigs were fed the low energy diet. The LRFI pigs were not inferior to the HRFI line, but their superiority was lost. This suggests that the selection of pigs for feed efficiency needs to consider the nature of the commercial diets that the pigs will receive when placed into a production system, although the low energy diet used here should be considered quite extreme in terms of energy density and fiber content.

Interestingly, the superiority of the LRFI pigs with respect to lower back fat thickness was observed in two of the three generations, irrespective of the diet fed. We only observed greater loin eye area in the LRFI pigs in generation 8 and that was independent of diet. In the later generations (9 and 10), no differences were observed. These also suggest no major changes in carcass composition between the two lines, but in those fed the lower energy diets, carcass quality was affected.

Carcass Composition and Meat Quality

As mentioned previously, concern has been expressed that pigs highly selected for improved feed efficiency may produce pork which is of inferior quality. Compared to a random control, LRFI carcasses have less fat (Cai et al., 2008; Lefaucheur et al., 2011; Faure et al., 2013) or tend to have less back fat (Smith et al., 2010; Boddicker et al., 2011a). When comparing animals that have been selected divergently, animals with improved feed efficiency (LRFI) produce pork with a lower post mortem pH and slightly poorer meat quality than HRFI pigs, according to a French study (Gilbert et al., 2007). Lefaucheur et al. (2011) and Faure et al. (2013) observed that water holding capacity and sensory quality, respectively, have been negatively affected by selection for LRFI. This is contradictory to data generated with generation five of the RFI lines from Iowa State University where results of LRFI carcasses had a lower percent lipid and higher percent moisture in the LM when compared to a random control line (Smith et al., 2011).

Carcass composition and meat quality from Iowa State University RFI lines in generation 8 were collected when animals were fed either a high or low energy diet. Arkfeld et al. (2013) observed that both RFI lines suffered an impact on carcass composition, and suffered minimal affect on pork quality and sensory characteristics. Even when fed a low energy diet, selection for increased efficiency did not compromise pork quality.

Protein Turnover

The more efficient RFI pigs tend to have less carcass fat, greater carcass lean, and lesser ADG compared with control and high RFI (Cai et al., 2008; Smith et al., 2011; Young et al., 2011). Increased protein and decreased fat composition in carcass from those pigs have been reported by Boddicker et al. (2011 a,b). Physiologically, pigs selected for low RFI and improved feed efficiency have reduced protein degradation and protein turnover than the HRFI pigs. Protein degradation pathways within muscle are decreased in the low RFI vs. high RFI pigs (Cruzen et al., 2013). These pathways include the calpain and the ubiquitin-proteasomal systems. Interestingly, these changes in protein degradation may be attributed to increased oxidative stress and mitochondrial reactive oxygen species production (Grubbs et al., 2013). A greater feed efficiency in LRFI pigs can possibly be explained by this lower rate of protein degradation and reduced oxidative stress.

Susceptibility to Immunological Stress

It is well known that pigs exposed to pathogens respond with reduced feed intake and growth rate (Johnson, 2012). When an animal is exposed to such a challenge, its metabolic priorities shift to an appropriate immune response. However, little data have been generated to evaluate the impact of selection for feed efficiency on disease susceptibility and immunological response. It has been theorized by some that selection for improved efficiency might make pigs more susceptible to disease. In order to test this, two studies have been conducted with the low and high RFI pigs. The first study utilized a Porcine Reproductive and Respiratory (**PRRS**) virus challenge in collaboration with Kansas State University. The second study analyzed how pigs responded to an inflammatory challenge using *E. coli* derived lipopolysaccharide (**LPS**).

Dunkelberger et al. (2014) analyzed the effect of PRRS, one of the more important disease concerns in pork production, on lines of pigs divergently selected for low or high RFI. Animals were challenged with PRRS, blood samples were collected and growth performance was monitored for 42 days post infection. Contrary to expectation, the impact of PRRS on the LRFI pigs was no worse than on the HRFI pigs, and in some instances

was actually less. These results suggest that pigs selected for increased feed efficiency based on RFI are not more susceptible to disease and, in fact, may be able to respond better to a disease challenge.

Rakhshandeh et al. (2012) evaluate the impact of repeated LPS challenges and divergent selection for RFI on apparent ileal and total tract digestibility (**AID** and **ATTD**) of nutrients, and intestinal nutrient transport and barrier function. Divergent selection for low RFI increases ATTD, but it has no effect on AID, of nutrients. However, immune system stimulation affects both AID and ATTD of dietary nutrients in pigs and may be a major source of feed efficiency variation. Altogether, it was concluded that genetic selection for LRFI reduces the total tract digestive capacity of growing pigs during immune system stimulation.

Response to Behavioral and Physiological Stress

There have also been questions regarding the selection of more efficient animals in terms of possible behavioral changes, especially with respect to fear and anxiety. Two tests conducted to evaluate fear were the novel object test and the human approach test. Jenkins (2013b) conducted the human approach and novel object test in both LRFI and HRFI pigs and concluded that pigs of the LRFI line took longer to approach humans and the novel object when compared to HRFI line, but after the first contact with the novel stimuli, both lines took the same time to approach, indicating that there is an initial response in LRFI. Both lines recover equally within 10 minutes (Figure 3-4), so the authors have concluded that the differences in these tests between the LRFI and HRFI lines are very small.

To further understand the endocrine differences between our two selection lines, grower pigs were catheterized and subjected to an adrenocorticotrophic (**ACTH**) challenge. When animals encounter an external stressor, corticotrophin-releasing hormone is released from the hypothalamus, stimulating the secretion of ACTH from the pituitary gland. ACTH secretion in turn stimulates cortisol release. According to Jenkins et al. (2013a), administration of exogenous ACTH induces an endocrine stress response and this response can be measured through blood levels of cortisol.

During an evaluation of the role of the ACTH-cortisol axis and the stress response, Jenkins et al. (2013b) found that HRFI pigs are actually more responsive than the LRFI pigs, but both cope equally well (Figure 5).

Conclusions

Even when fed a low energy diet, RFI showed to be a promising outcome as a selection tool for increased efficiency without compromising pork quality. Our multidisciplinary study is still in progress but we can already conclude that pigs highly selected for improved feed efficiency over multiple generations can withstand nutrition, immunological and behavioral stresses, comparable to pigs that had not been so selected.

Acknowledgments

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Table 1. List of research scientists included on the AFRI Feed Efficiency project.

Name	Institution	Country
Dr. Lloyd Anderson	Iowa State University	U.S.A.
Dr. Roger Campbell	Pork Cooperative Research Center	Australia
Dr. Jack Dekkers	Iowa State University	U.S.A.
Dr. Joel DeRouchey	Kansas State University	U.S.A.
Dr. Frank Dunshea	The University of Melbourne	Australia
Dr. Nicholas Gabler	Iowa State University	U.S.A.
Dr. Helene Gilbert,	Institut National de la Recherche Agronomique	France
Dr. Anna Johnson	Iowa State University	U.S.A.
Dr. Brian Kerr	USDA	U.S.A.
Dr. Peng Liu	Iowa State University	U.S.A.
Dr. Elisabeth Lonergan	Iowa State University	U.S.A.
Dr. Steven Lonergan	Iowa State University	U.S.A.
Dr. John Mabry	Iowa State University	U.S.A.
Dr. Dan Nettleton	Iowa State University	U.S.A.
Dr. John Patience[1]	Iowa State University	U.S.A.
Dr. Max Rothschild	Iowa State University	U.S.A.
Dr. Raymond Rowland	Kansas State University	U.S.A.
Dr. Mike Tokach	Kansas State University	U.S.A.
Dr. Chris Tuggle	Iowa State University	U.S.A.
Dr. Andrew van Kessel	University of Saskatchewan	Canada
Dr. Tom Weber[2]	USDA	U.S.A.

[1] Project Director
[2] Resigned in 2013 when he left the employment of USDA for a position in the private sector.

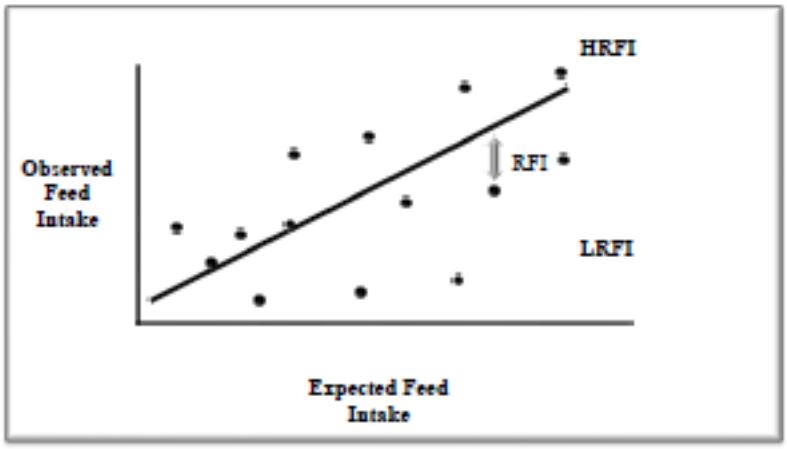

Figure 1. RFI can be calculated as observed feed intake minus expected feed intake (Koch et al., 1963; Kennedy et al., 1993).
Source: Arkfeld, 2013

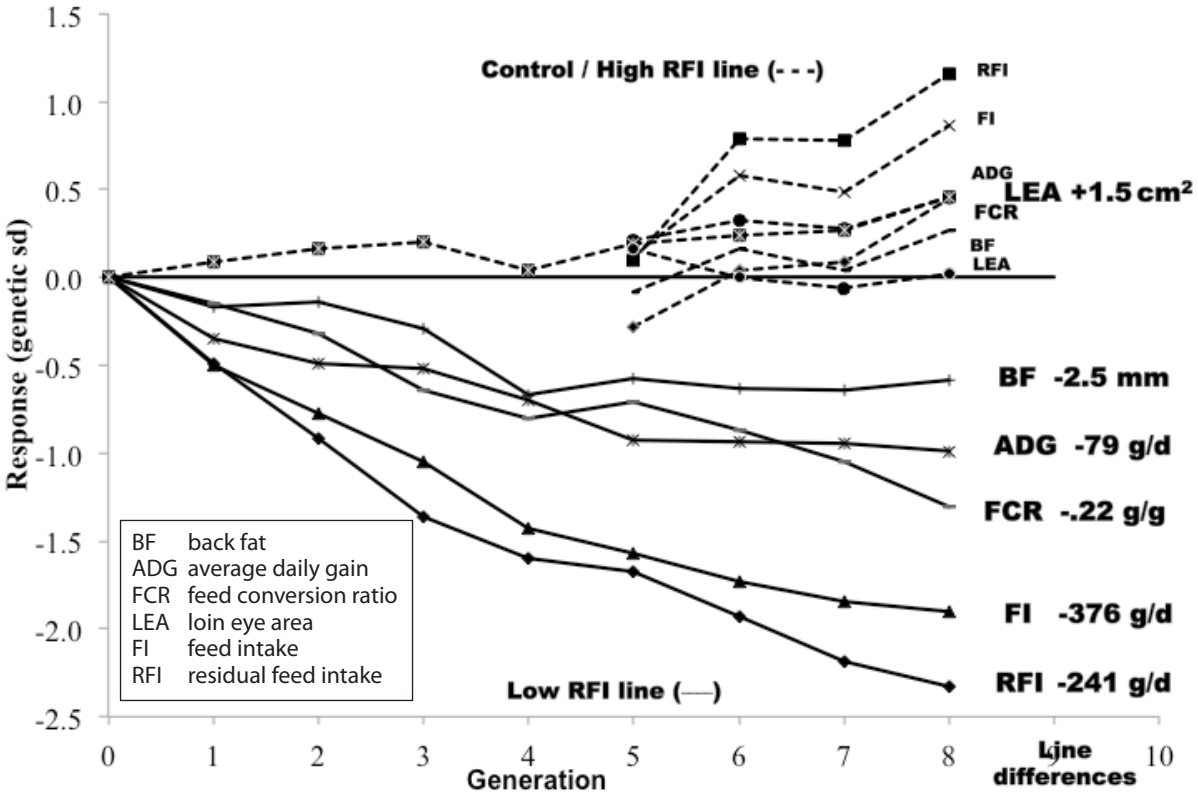

Figure 2. Response to selection for residual feed intake. Line difference are LRFI—HRFI.
Source: Young & Dekkers (2012).

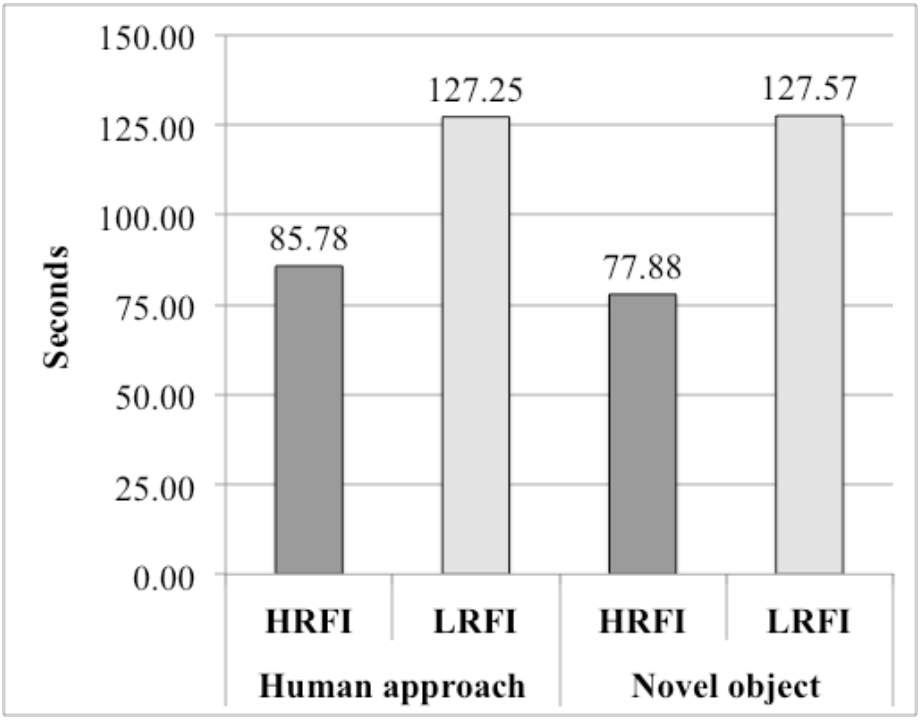

Figure 3. Latency to first human/object touch of barrows divergently selected for RFI.
Source: Jenkins et al. (2013a)

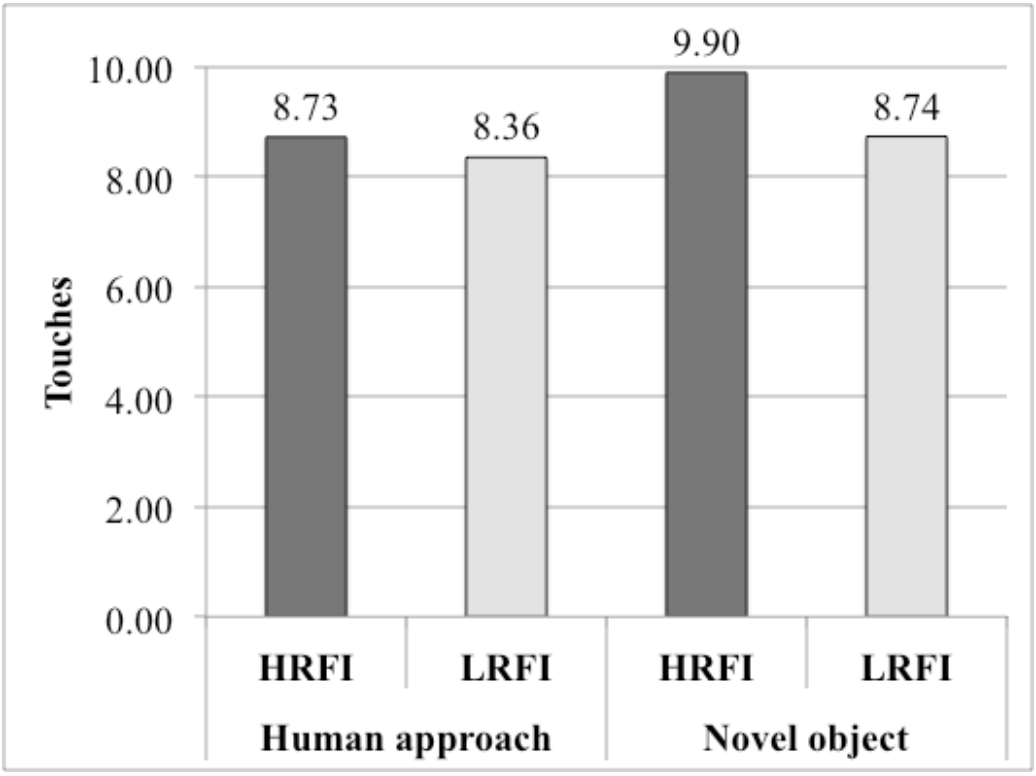

Figure 4. Total number of human/object touch of barrows divergently selected for RFI.
Source: Jenkins et al. (2013a)

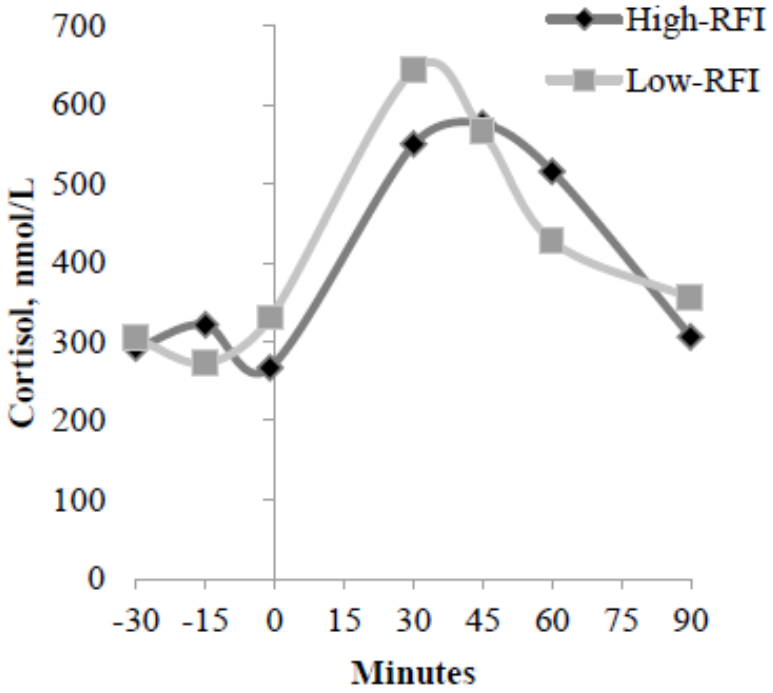

Figure 5. Cortisol concentration over ACTH challenge of gilts divergently selected for RFI.
Souce: Jenkins et al. (2013b)

Speakers at Last Year's Conference

William Weldon, Elanco Animal Health, Keynote Speaker

Jeffrey Andresen, Michigan State University

Ronald Ball, University of Alberta

Ryan Dilger, University of Illinois

Jon Ferrel, Elanco Animal Health

Lee Johnston, University of Minnesota

Scott Radcliffe, Purdue University

Jerry Shurson, University of Minnesota

Merlin Lindemann, University of Kentucky, Moderator

Last Year's Conference

Attendees enjoying lunch.

Aaron Gaines (The Maschhoffs) visits with Don Orr (JBS United).

Tip Cline (Purdue) and Don Mahan (Ohio State) going through the food line.

Roast pork loin lunch.

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