The Midwest Feeds Consortium

Final Report

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Robert Summerfelt, Keith Heffernan, and Phillip J. Kaus

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Critical to the success of any animal rearing technology is a consistent and reliable supply of nutritious and cost-effective feeds. The United States is a world leader in producing and processing feed grains and formulating feed for warm-blooded farm animals. Considerable progress has been made, using similar inputs and technologies, in formulating and manufacturing feeds for catfish and trout in freshwater aquaculture systems. However, little progress has been made on feed formulation for other aquaculture species, particularly marine species. Special challenges and opportunities include marine fish and shrimp diets that are heavily dependent on marine meals (fish, squid, shrimp, etc.), and the growth performance of aquatic species being fed diets high in plant-based ingredients.

The objective of this multiyear research and development project, conducted by the Midwest Feeds Consortium (MFC), was to provide appropriate biological and economic information on the effectiveness of grain, oilseed, and animal coproduct-based protein meals common to the United States Midwest as replacements for marine meals in aquatic animals feeds. The quality, cost, and availability of marine meals are generally recognized as growing constraints worldwide. The United States has a substantial competitive advantage in feed grain technology and production, which can be leveraged to strengthen the competitiveness of the U.S. grain and feed industry provided that appropriate marine meal substitutes are found or developed. The work reported here established a basis for advancement in feeds and ingredient technology development for aquatic species as well as an economic assessment of the potential for the U.S. grain and oilseed industries.

This project was initiated in September 1994, with approval of a one-year proposal and work plan. This work plan included a workshop held in Des Moines, Iowa, of both industry and project participants that established the framework for consortium activities. In June 1995, a second year of funding was approved to initiate the bulk of the research and development activities. In close cooperation with consortium members and with the approval of the United States Department of Agriculture/Cooperative State Research, Education, and Extension Service

(USDA/CSREES), the second year work plan was modified with respect to particular ingredients and processes originally chosen, in light of revised expectations and potential opportunities.

A total of one annual and five semiannual reports were submitted to CSREES over the four-year period of this project. This highlight report describes findings and accomplishments of special significance as judged by the investigators. The highlight report includes identification, discussion of priority findings and accomplishments, impact on direction and analysis, overall ¡mpact, and research needs and opportunities.

THE MIDWEST FEEDS CONSORTIUM

Final Report

Introduction

The strategic intent of the Midwest Feeds Consortium (MFC) was to decrease the dependence of the U.S. agriculture and aquaculture feed industries on imported marine protein meals and to increase the utilization and export of plant and animal coproduct protein meals to the international aquaculture industry. Replacement of marine meals in feeds traditionally dependent on these protein sources with grains, oilseed, and animal coproduct protein meals common to the U.S. Midwest would be accomplished through innovative, value-added ingredient processing technology. Through systematic, integrated, industry-directed research to develop ingredient composition, quality, digestibility, and economic values, the U.S. and international feed industry would then be able to rapidly incorporate the findings into their ingredient and equipment-purchasing decisions. The work described herein drew heavily upon recommendations developed by the MFC workshop, which was the first United States Department of Agriculture (USDA)-funded undertaking by the Consortium. The priority activities were industry linkages, ingredient processing, ingredient testing, and technology transfer. After the initial workshop, the Consortium underwent several changes in management structure, participants, and directions, which slowed progress considerably. In May 1997, a focus meeting was held in Des Moines, Iowa, between principal Consortium participants to modify priorities and reestablish timelines. The project reemerged with objectives designed to meet the priority issues of the project.

The second section of this summary final report provides an overview of the MFC project. This includes highlights of the two proposals submitted in January 1994 and July 1995. This documentation shows the overall intent of the project and relationship of the workshop in establishing the fundamentals of the project research and development phase. Described separately are the circumstances that led to modifications of the project needed to meet project

objectives. The section also includes a listing of institutions that collaborated on this ingredient development project.

The third section addresses priority technical findings and accomplishments. This section briefly reviews advances made in industry linkages, ingredient processing, ingredient testing, and technology transfer. It provides verification for across-species utilization of ingredients tested and, in some cases, economic incentive for substantial replacement of the marine meal portion of the test diet utilized. A comparative analysis of a multi-ingredient, regression-based digestibility assay with a more commonly used single ingredient replacement assay is also provided. This section provides evidence that a regression-based assay may provide more meaningful information for feed manufacturers in preparation of least cost diet formulations for aquatic species.

The fourth section outlines the needs for future research. The MFC was intended to be a multiyear undertaking, with initial phases designed to establish the necessary groundwork for ingredient evaluation and testing as well as industry linkages and technology transfer. Although subsequent funding was not secured, results of the initial work clearly indicate the potential for use of value-added grain and oilseed products in diets for aquatic species, at least those ingredients of commercial interest within the Midwest portion of the continental United States. Marine meal replacement remains a critical issue for the aquaculture feeds industry, and represents additional opportunities for the export of U.S. grains and oilseed products.

An annual report with a workshop Proceedings was submitted to CSREES for the period December 1994 through November 1995. Semiannual reports were submitted for the periods December 1995 through May 1996; June 1996 through November 1996; December 1996 through May 1997; June 1997 through November 1997; and December 1997 through May 1998.

For the purposes of this highlight report, all findings and accomplishments identified and discussed in the reports were reviewed by each of the current investigators and participants. They were asked to identify and prioritize the most important or useful findings and accomplishments. These priority findings and accomplishments are included in the third section, and the continuing needs and opportunities are presented in the fourth section.

Research Plan And Organization

In this section, the research plan and organization are reviewed. This is outlined in two parts: (1) an overview of the MFC, based on proposals and modifications, and (2) a listing of Consortium members.

Overview of the Midwest Feed Consortium Project

The first proposal was submitted in January 1994. The second proposal was submitted in July 1995. The material presented provides a picture of a project that established clear objectives but required modification as changing circumstances, new information, and more relevant questions arose.

Proposal, January 1994. It is generally understood that the development of aquacultural feeds, as compared with agricultural feeds, presents new challenges and opportunities. Industry participation in the project was assumed critical to help establish guidelines and protocols for research and development activities that would yield results acceptable to eventual end-users. The priority objectives were to coordinate and hold workshops and to publish and distribute workshop proceedings.

Participation of key industry sectors and scientists to plan the activities of this Consortium was considered highly advantageous. The intent was to bring together experts in aquaculture and terrestrial animals nutrition, feeds processing, equipment manufacturing, and ingredient development to build consensus on research and development approaches. Some key issues that needed to be discussed were choice of species, testing protocols, priority ingredients, and processing alternatives. The expected result was that new ideas and approaches would be generated, stimulated by the diversity of opinions that would be shared in a single setting. Research and development activities were to be guided heavily by the recommendations of the workshops. Two workshops were planned on consecutive days to address issues relating to (1) Ingredients/Processing and (2) Ingredient Assays.

Key to technology transfer goals and to maintaining industry participation throughout the Consortium was the dissemination of workshop proceedings to participating members and other industry members. The intent was to publish and distribute as a Proceedings the presentations

given and the results of section breakout meetings. This would stimulate further thought by participants to provide additional input and would encourage others who did not participate to contribute to the evolving project.

Proposal, July 1995. The second phase of work included execution of research and development activities as recommended by the workshop. Specific research and development activities were established for four primary areas that would initiate ingredient testing and evaluation with diverse species and establish a basis from which expansion of MFC activities could occur. These areas were (1) Industry Linkages; (2) Ingredient Processing; (3) Ingredient Testing; and (4) Technology Transfer.

- Rapid adoption by the aquaculture industry of Consortium results is a hallmark criterion by which elements of the project were selected and molded. Associations with industry groups, such as grain and oilseed commodity groups, aquaculture feed producers, and milling equipment manufacturers, were to be sought and kept abreast of Consortium activities. In addition, a database of national and international aquaculture feed ingredient and feed machinery purchasers would be created. This database would be provided to U.S. ingredient and equipment producers for their use in contacting potential customers. Work was also targeted to develop and calibrate a methodology to estimate own and cross-price elasticities of fish meal substitutes and to develop baseline projections for trade and prices in meat, feed grain, and soybean meal. A second workshop meeting at the end of the project would also be held to apprise Consortium participants of results to date.
- The feeds industry can be characterized as one that converts food production coproducts into animal feeds. Processing those products to improve nutritional value and digestibility is an important step toward increasing their utilization and reducing pollution loads. Research was targeted to develop animal coprocessing technology using whole blood and corn and/or soybean meal. In addition, work was scheduled to develop methods to modify corn gluten meal to increase its utilization by aquatic animals and to develop a low-cost soybean protein concentrate. Once evaluated both biologically and economically, processes were to be scaled-up for pilot plant production.

- A key component to the project was the determination of biological feasibility of products developed and characterization of digestibility values for feed formulation. The Consortium workshop strongly endorsed the idea that all test feeds should be produced at one facility and that analyses of ingredient, finished feed, fecal, and body composition samples be performed only in labs that routinely perform large numbers of such analyses. In addition, common protocols for conducting biological evaluations including standardized methods for collection of fecal material for digestibility determinations, were endorsed because of the variety of species being tested. All ingredients to be tested were to be sent to a qualified lab for proximate analysis and determination of amino acid, fatty acid, and microingredient composition. Diets would be formulated, processed, and fed to four selected species, representative of diverse aquaculture sectors and economic opportunities. These species included the rainbow trout *(Oncorhynchus mykiss),* Pacific threadfin *(Polydactylus sexfilis),* hybrid striped bass *(Morone saxatilis),* and Pacific white shrimp *(Penaeus vannamei).* Broiler chicks would be used as a reference terrestrial animal.
- The ultimate success of the Consortium is reflected in the extent of industry application of the developments made. Application requires that industry be kept abreast of Consortium activities through rapid dissemination of results and developments. This was to be accomplished by documentation of research results through normal, scientific peer-reviewed channels and through publication of a technical bulletin that would provide industry more rapid access to Consortium findings. In addition, disk copies of an ingredient database for aquaculture would be upgraded and disseminated to interested parties.

Participants in the 1994 workshop were particularly interested in the results of soybean blends with animal slaughter byproducts and new genetic engineered soybean products. Of particular interest were the low-oligosaccharide soybeans. The soybean oil meal and slaughter byproducts blends were readily available, and diet development and fish trials started on schedule with a soybean meal red blood cell mixture. However, the low-oligosaccharide soybeans provided a substantial challenge. Although the Center for Crops Utilization and

Research (CCUR) felt they could develop these properties in the laboratory, patent rights to this variety of beans were held by DuPont. Any work to secure or develop the properties exhibited by low-oligosaccharide soybean varieties was halted until Iowa State University patent attorneys could determine proper operating procedures. This was a lengthy and frustrating delay to the research activities. It resulted in recommendations by patent attorneys to establish an agreement with DuPont, which was accomplished. Although Iowa State University and Kansas State University signed the agreement, the other partners in the Consortium found it unacceptable for various reasons to become part of the agreement. Therefore, low-oligosaccharides were tested only with the striped bass. As a result, the work plan was modified to test corn gluten meal in the fish feeding trials for the four species. It is significant to note, however, that this project did thrust Consortium members into one of the most challenging questions regarding proprietary information from private sector companies and individuals.

Consortium Members

The MFC was conceived as a means to bring together the strength of ingredient development of the Midwest with a strong approach toward applied aquaculture feeds development. Two Consortium members took the lead roles in development and implementation of the project:

Iowa State University, with its focus on the production and trade of grains, oilseeds, and animals products, and its long history of performing value-added research with products of the Midwest as well as defining the economic impacts of agriculture trade and processes; and

The Oceanic Institute, with its international reputation as a key player in the development of applied aquaculture feed and processing technologies.

Personnel responsible for project implementation, however, changed numerous times over the course of the project, and several members resigned altogether. An overview of the Midwest Feeds Consortium organizational structure, mode of interactions, and research areas is provided in Figure 1.

Iowa State University (ISU). ISU served as the primary administrative and coordinating entity in the project and also conducted a major portion of the project development activities. Several in-house subcontracts were established with the Center for Agricultural and Rural Development (CARD), which was responsible for planning and coordinating activities. The Center for Crops Utilization and Research which is involved in the utilization of Midwestern-grown products was responsible for ingredient development. The Department of Animal Ecology performed the fish trials for striped bass.

Corporation for International Trade (CIT). The CIT of Des Moines, Iowa, finds new markets for Midwestern agricultural and agribusiness products, and develops new uses for agricultural commodities. Its primary responsibility for the MFC was to maintain contacts with industry and governmental agencies, organizing workshops, report preparation, and coordination of all participants.

The Oceanic Institute (OI). The OI served as Testing Coordinator for the project, ensuring analyses of products to be tested as well as the formulation, production, and distribution of diets to other testing partners. The OI was also responsible for conducting biological tests on the Pacific threadfin and Pacific white shrimp. A subcontract with CN Laboratories (CN Labs) of Courtland, Minnesota, for compositional analyses was established.

Purdue University (PDU). PDU was chosen to conduct biological tests on rainbow trout because of their experience and qualifications with the species.

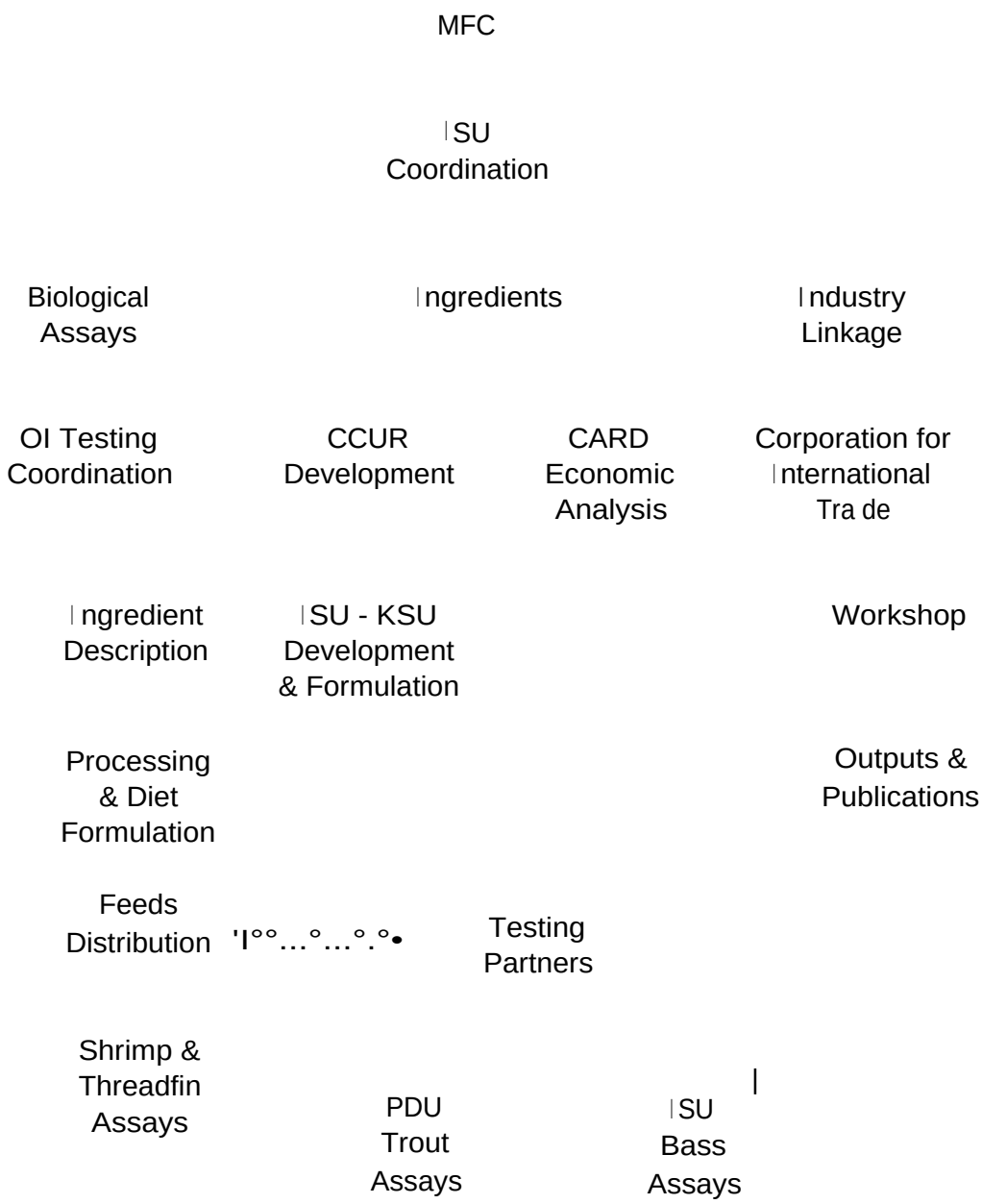

Figure 1. Overview of the Midwest Feeds Consortium.

Legend.

MWF	= Midwest Feeds Consortium	CCUR	= Center for Crops Utilization Research
ISU	= Iowa State University	CARD	= Center for Agricultural and Rural Development
of	= Oceanic Institute	KSU	= Kansas State University
PDU	= Purdue University	CIT	= Corporation for International Trade

The Workshop: **Expanding Agriculture Coproduct Uses in Aquaculture Feeds**

The workshop held on December 5-7, 1994, initiated the planning and development stage for the MFC. It was well attended by a diverse group of scientists and industry members representing various sectors of agribusiness.

Priority Findings and Accomplishments

Priority Findings

The MFC project was initiated with a planning workshop of experts in the agriculture and aquaculture communities. Results led to the definition of target ingredients, species, and processes for the implementation stage. Toward that end, advances were made in defining new ingredients for use in the aquaculture industry. The highlights of technical findings and accomplishments toward product development as prioritized by Consortium participants are provided. Differences in utilization of ingredients tested were found, but responses among species were generally similar. This suggests the universal application of ingredients in the aquaculture industry, at least among those species that fall into the model groups tested. Evidence is also provided to support the use of a multiple regression approach for determination of ingredient digestibility values for aquatic species that would aid in least-cost formulation analyses.

Coordinate and hold workshops. The very successful workshop conducted from December 5-7, 1994, in Des Moines, Iowa, gave industry leaders from ingredient producers, feed processing equipment manufacturers, feed millers, and farmers a forum to review industry advances and to influence MFC planning. Representatives from companies such as Archer Daniels Midland, DuPont, Continental Grain, California Pellet Mill, Wenger, Insta-Pro, Ralston Purina International, Zeigler Brothers, and Rangen were active participants in workshop activities. In addition to the fifteen speakers from industry, there were nine others from industry that attended and participated in the breakout sessions.

A full accounting of the workshop activities, presentations, and breakout sessions is included in the MFC workshop summary document provided as part of an annual report to CSREES in February 1996. Of particular note are the choices of animals and ingredients to be

tested. Representative species were chosen to account for a wider base, including Pacific threadfin as a model for warm-water carnivorous species, the hybrid striped bass as a model for brackish water species, and the Pacific white shrimp as a model for marine crustaceans. The rainbow trout was chosen as a reference species because of the considerable body of evidence already present on ingredient digestibility and utilization, and because it also represented a significant cold-water finfish model. It was also considered prudent to include broiler chicks as a terrestrial animal reference, at least for one of the ingredients tested. Several ingredients and processes were chosen but had to be modified as the project progressed. Ingredients are explained in the subsection entitled Ingredient Processing.

Publish and distribute workshop proceedings. The MFC workshop summary document, "Expanding Agriculture Co-product Uses in Aquaculture Feeds," was prepared following the workshop and distributed to 200 members of academia and industry who requested copies. A database of industry contacts was compiled from these inquiries and from the American Feed Industry Association (AFIA) Aquaculture Committee contacts. Existing CIT contacts throughout the Midwest total over 3,500 U.S. companies; of those, approximately 650 have interests in expanding agriculture coproduct uses. The database will serve to link the Consortium with industry through MFC publications.

Industry linkages. The primary purpose of the economic feasibility analysis was to evaluate the market potential of the newly developed protein feed products. Given the results of the fish feeding trials, and using preliminary assumptions on feed processing costs, each alternative ingredient was studied to determine if an adequate price could be charged to cover the costs of feed production. To provide this analysis, a database and a quantitative economic evaluation model were developed. These tools provided estimated breakeven prices (prices that must be charged to cover production costs) for the various feed product mixtures for each of the fish species tested.

The analysis of market potential, although preliminary in nature, provides valuable information on those products that show market promise, clearly identifies markets potential by species, and sheds light on where to focus further research. The derived synthetic demand showed that there exists a probable demand for crop and animal coproducts as substitutes for fish

meal. The partial budget analysis allowed an examination, at a static point in time, of the economic incentives of utilizing crop and animal coproduct technology. Results showed there would be economic benefits for utilizing soybean-based products, implying there is a potential new demand for these crop and animal coproduct feedstuffs. Results indicated that soybean-based products can legitimately constitute 30 percent of a fish diet without hindering performance and decreasing costs This could translate into an annual increase in soybean demand of approximately 2 percent.

Ingredient processing. The ingredients developed during this project were based on three major byproducts of Midwestern agriculture: red blood cells from swine, corn gluten meal from wet-corn milling, and stick water from the animal rendering process. In all the ingredients developed, physical, chemical, and nutritional characterizations were performed. The best ingredients developed from the red blood cells and corn gluten meal were sent to the researchers in charge of the animal tests. All of these experiments were conducted in the laboratories of the Grain Science and Industry Department at Kansas State University, Manhattan, Kansas, and in the pilot plant facilities of the Center for Crops Utilization Research at Iowa State University, Ames, Iowa.

The objective with the red blood cells was to come out with a stable ingredient that would have a longer shelf life, could be handled, and would be easy to add to the feed formulation. The red blood cells were utilized as a major source of protein and amino acids and were tested under mixing, dehydration, and extrusion processes. In the first development, red blood cells were mixed with soybean meal and the ratio of soybean meal and red blood cells was evaluated. In the second development, the red blood cells were mixed with particle-size reduced soybean meal, thus increasing the surface area. In the particle-size reduced material, more red cells material was added to the mixture, increasing the protein and amino acid content of the sample. The third development consisted of a two-part extrusion process: the first part was done in a laboratory extruder; the second part was done in a large-scale, low-cost extrusion system. In all three processes developed, dehydration was used at different levels to reduce the moisture content of the blend.

The second byproduct used in this study was corn gluten meal. The major objective was to reduce or eliminate the carotenoids, specifically the xanthophylls, in the corn gluten meal so these pigments would not affect the fish flesh. In order to achieve the reduction of the carotenoids, a lab procedure was developed. Three alternative methods were used to remove the carotenoids: removal with ethanol, methanol, and soybean flour. The most practical and least expensive method was selected for scale-up; this was the mixing with soybean flour at a 5 percent level. The large-scale carotenoid reduction of corn gluten meal was tested on several mixing systems that included a homogenizer and two different mixers. The resulting material was spray dried at three different temperatures in which different carotenoid reductions were achieved.

The third byproduct used in this study was stick water. The stick water was mixed with the soybean meal and then extruded in a laboratory scale extruder. The material was only tested for proximate characterization and amino acid content. No animal tests were conducted with the stick water.

Ingredient testing. The primary purpose of ingredient testing was to determine the relative biological response across species fed target ingredients and to estimate digestibility coefficients for those ingredients. Discussions held during the MFC workshop indicated that standardized protocols for completion of biological assays were desired, despite the variety of species chosen for testing. Because of similarities in dietary macronutrient requirements, it was decided that one formulation be utilized for all fish species. Separate diets would be utilized for shrimp and for broiler chicks. Test plant ingredients were added via linear programming to a reference formulation balanced on an isocaloric, isonitrogenous basis. This meant that other dietary ingredients in the reference formulation had to be adjusted appropriately as well. This method was contrary to digestibility protocols that have been used previously, which target replacement of only a portion of the entire diet regardless of nutritional composition. Concern had been raised previously that digestibility values calculated using the single level replacement method (termed the "Guelph" approach) were not accurate for all levels of inclusion that might arise in least-cost formulation analysis. It was argued that a multiregression approach to determine digestibility coefficients would be more meaningful, particularly if diets were balanced

appropriately to account for confounding effects on digestibility brought about by differences in diet energy or nitrogen content. Both methods were employed for verification Ingredients were added singly or simultaneously at graded levels (0, 33, 67, and 100 percent of maximum input level) depending upon limitations imposed by the macronutrient requirements of the test species. The Guelph approach employed replacement of 30 percent of the total reference diet with the test ingredient.

Multiple regression analysis employing backward elimination developed a relationship between inclusion levels of individual ingredients and diet digestibility coefficients. Digestibility data of diets fed to four species-hybrid striped bass, threadfin, shrimp, and rainbow trout-were used in the analysis. Results showed energy, protein, and dry matter digestibility coefficients of SBM/RBC diet fed to the four species could be predicted from the linear combinations of individual ingredients. In addition, the digestibility coefficients of all diets (ref trial, SBM/RBC, CGM) fed to threadfin and shrimp could be adequately predicted from the inclusion levels of individual ingredients used in the diets (corn starch, wheat flour, soybean meal, fish meal, fish oil, SBM/RBC, and white corn gluten meal). Digestibility data from the rest of the diets either did not reflect any significant effect of the linear combinations of individual ingredients or did not have enough observations for multiple regression analysis. In general, these results suggest that the digestibility coefficients of a diet vary relative to the inclusion level of individual ingredients and the relationship can be predicted by multiple regression-backward elimination analysis. The ability of the regression equations to predict digestibility coefficients was tested by comparing the predicted values with measured values from the Guelph method. Overall, results indicated that measured and predicted digestibility values are strongly correlated ($r = 0.97$).

However, the predicted digestibility values tend to be lower than the Guelph measured digestibility values. Generally, these observations suggest that the regression equations can be used to predict digestibility values comparable with Guelph measured values. However, the use should be restricted within the range of ingredient inclusion levels utilized in the development of the regression model.

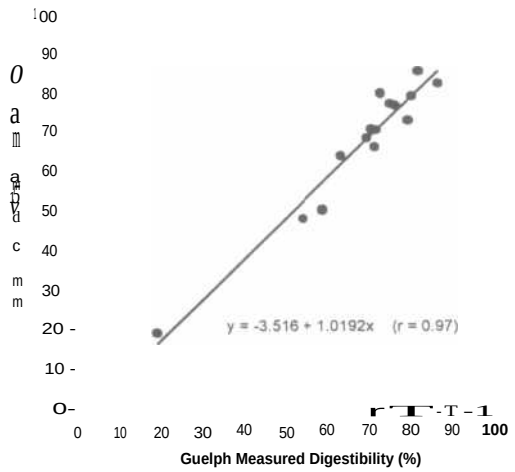

Figure 2. Regression predicted digestibility values (energy, crude protein, dry matter) as compared with Guelph measured digestibility values.

The reference diet formulation was used to provide baseline information on utilization of fish meal, soybean meal, and wheat flour. Results indicated that digestibility coefficients of the 10 diets formulated with varying levels of soybean meal and wheat flour did differ depending upon inclusion level. Animal response across species was also similar. Inclusion of soybean meal at or above 55 percent of the diet resulted in adverse effects on growth, whereas replacement levels for hi-gluten wheat flour caused no significant effects on growth or feed conversion. For Pacific threadfin, superior results were obtained when fish meal was replaced with a combination of 27.4 percent soybean meal and 26.0 percent hi-gluten wheat flour. Biological response of Pacific white shrimp was also better when some level of plant ingredients replaced fish meal. Results indicated that a significant part of the fish meal portion of diets for aquatic species can be replaced with soybean meal and hi-gluten wheat flour. The relative consistency in responses indicated the universality of the usefulness of the ingredients and likelihood that similar responses might be expected in other species represented by the models. In general, however, digestibility values measured for hybrid striped bass were substantially lower than those for the other species. This may be due to the fact that feces from these fish

were hand stripped instead of collected off the tank bottom as was the case for the other species tested. Differences in collection methods of feces for aquatic species typically result in over- and/or underestimates of digestibility values.

Results of the fish and shrimp trials indicated that the SBM/RBC product tested was a good substitute for fish meal in the diets tests. Utilization of SBM/RBC product across species was generally similar. No adverse effects were observed in either growth or feed conversion at levels up to 33.7 percent of the diet. In fact, there was a significant improvement in growth of hybrid striped bass fed the diet containing 16.6 percent SBM/RBC. Growth and feed conversion were adversely affected in all species when the level of SBM/RBC reached 50 percent of the diet. Except for hybrid striped bass, digestibility coefficients for all parameters measured generally were unaffected by an increasing level of SBM/RBC. Digestible energy values were around 3,700 kcal/kg for threadfin, 3,246 kcal/kg for shrimp, 3,879 kcal/kg for trout, and 2,570 kcal/kg for hybrid striped bass based on the Guelph method. Several factors for reduced performance at the highest dietary inclusion level could have included an amino acid imbalance, high dietary iron content, or low available phosphorus content.

In contrast, the SBM/RBC product was not as good an ingredient for broiler chicks when compared with chicks fed diets containing fish meal. The ME„ of the fish meal tested was 4,680 kcal/kg, a relatively high value, when included at 5-15 percent in a corn-soybean meal-based diet for 1 to 14-day-old broiler chicks. The ME„ value of SBM/RBC for chicks was about 3,115 kcal/kg when fed at 5 percent or 10 percent of the diet. The value, however, was only 1,767 kcal/kg when it constituted 15 percent of the diet, suggesting that, at this dietary concentration, SBM/RBC may have impaired the utilization of energy from other ingredients. The difference in results between chicks and the aquatic species tested indicates the importance of establishing digestibility values specific for aquatic species.

Decolorized CGM was generally not a good replacement for fish meal in diets of the aquatic species tested. Lowered performance was observed in all species with increasing dietary levels. In contrast to the SBM/RBC product tested, lowered performance of animals fed the CGM could be linked to lowered digestibility coefficients, indicating that increasing dietary levels did affect digestibility of the other dietary ingredients. This was especially true for the 40 percent inclusion

level, which for shrimp, reduced digestible energy value of the diet by nearly 20 percent. Digestible energy coefficients were around 3,484 kcal/kg for threadfin, 4,510 kcal/kg for shrimp, and 2,835 kcal/kg for hybrid striped bass based on the Guelph method.

The crude protein (50.9 percent), fat (1.58 percent), and gross energy content (4,547 kcal/g) of low-oligosaccharide SBM was slightly higher than that of conventional SBM, but crude fiber, stachylose (<0.2 percent), and raffinose (<0.2 percent) was much lower than conventional SBM. The four experimental diets containing the low-4 SBM contained similar concentrations of the most critical essential amino acids (i.e., arginine, lysine, and tryptophan) to that of the reference diet; however, the concentration of methionine declined in proportion to the inclusion rate of the low-4 SBM, the diet containing 50 percent low-4 SBM had a methionine concentration of 0.769 compared with 1.005 for the reference diet.

Compared with the reference diet, all measures of fish growth showed an increase in growth rate with inclusion of the low-4 SBM up to 33 percent inclusion, but the diet with 50 percent inclusion had lower growth rate than the reference diet. Apparent digestibility of CP and GE for the low-4 SBM was 80.3 percent and 96.8 percent, respectively. Net protein utilization (NPU), protein efficiency ratio (PER), and energy retention (ER) of hybrid striped bass fed diets with low-4 SBM were equal to or greater than those of the reference diet for all diets containing low-4 SBM, except that of the diet that contained 50 percent low-4 SBM. The low-4 SBM was a useful replacement for fish meal up to an inclusion level of 33 percent, an inclusion level similar to that found for standard SBM in experiment 1.

Multiple regression analysis employing backward elimination procedure was used to develop a relationship between inclusion levels of individual ingredients and diet digestibility coefficients. Digestibility data of diets fed to four species-hybrid striped bass, moi, shrimp, and rainbow trout-were used in the analysis. Results showed that the energy, protein, and dry matter digestibility coefficients of SBM/RBC diet fed to the four species can be predicted from the linear combinations of individual ingredients. In addition, the digestibility coefficients of all diets (ref trial, SBM/RBC, WCGM) fed to moi and shrimp can be adequately predicted from the inclusion levels of individual ingredients used in the diets (corn starch, wheat flour, soybean meal, fish meal, fish oil, SBM/RBC, and white corn gluten meal). Digestibility data from the

rest of the diets either did not reflect any significant effect of the linear combinations of individual ingredients or did not have enough observations for multiple regression analysis. In general, these results suggest that the digestibility coefficients of a diet vary relative to the inclusion level of individual ingredients and the relationship can be predicted by multiple regression-backward elimination analysis.

The ability of the regression equations to predict digestibility coefficients was tested by comparing the predicted values with measured values from the Guelph method. Overall, results indicated that measured and predicted digestibility values are strongly correlated ($r = 0.97$). However, the predicted digestibility values tend to be lower than the Guelph measured digestibility values. Generally, these observations suggest that the regression equations can be used to predict digestibility values comparable with Guelph measured values. However, the use should be restricted within the range of ingredient inclusion levels utilized in the development of the regression model.

Technology transfer. Continued interaction has taken place between the research team and the feed formulation industry and feed equipment manufacturers. Much of this interaction has been on an informal basis. However, copies of research papers and semiannual reports have been distributed upon request to these companies and individuals. Of particular importance to these entities is the economic analysis of the test products that has not been available until the completion of this report. Several firms have followed the progress of this research project closely to ensure that they could adopt useful results from this project. It is anticipated that several additional technical bulletins will be published by the researchers that will be of particular interest to the feed formulation companies, as well as the final report that will present the entire database.

Comparison of Feeds for Aquatic and Terrestrial Farm Animals

The fish meal trap. Justification for this work was the growing concern among the aquaculture and feeds industries about world supplies of marine protein meal (specifically fish meal) and the high dependence on it for production of aquaculture feeds. Worldwide, the food and feed industries use approximately 5-6 million metric tons of fish meal annually (Anon., 1998a,b).

For example, the single largest agricultural import into the United States in 1987 was fish meal at $3.1 billion (Anon., 1989b). Fish meal is the principal ingredient in most commercial aquaculture feeds and is also important in poultry and swine feeds. In 1992, poultry feed production in the United States reached 40 million tons, using 40 percent of the fish meal supply (Rumsey, 1993). Although the dependence on fish meal by terrestrial animal diets has been decreasing, the fish and shrimp culture industry, which is growing worldwide at an annual rate of 11 percent (Tacon, 1997), is still critically dependent on fish meal as a feedstuff. New and Wijkstrom (1990) calculated that for every kilogram of intensively farmed fish and shrimp, three kilograms of "raw" (captured) fish is needed for feed.

There is a consensus that world fish stocks are being harvested at or above their sustainable yield (New, 1991; Anon., 1997; Bailey, 1997); a global annual harvest near 100x10 6 metric tons has been an accepted figure for several decades. New and Wijkstrom (1990) talked of a "fish meal trap": the larger the aquaculture industry grows, the more vulnerable it becomes to fish meal availability. Tacon (1997) estimated that world aquaculture feed production will increase from approximately 8.6x10 6 metric tons (in 1995) to 15.6x10 6 metric tons by the year 2000. The conclusion is that future growth in industries dependent on fish meal will be jeopardized; all other agriculture production affected by fish meal price and availability will also be affected. Thus, it is necessary to evaluate both the direct cost reduction at the firm-level due to fish meal substitution and the economic relationships between the primary input-output sectors likely to be affected.

As part of Chamberlain's (1993) description of the aquaculture industry, he defined several research needs. These can be summarized in two categories: (1) find ways to make fish meal more cost-effective, and (2) replace fish meals with other protein sources. There is a history of finding substitutes for fish meal in formulations for both aquatic and terrestrial feeds to decrease reliance on fish meals. Because grain and oilseed meals are considerably cheaper on a unit protein basis, less volatile in price (availability), and more consistent in quality, there is a considerable incentive for feed processors to include as much plant meal as possible. When the nutritional and nonnutritional problems associated with fish meal substitution are solved,

economic forces in the marketplace will cause this changeover to occur, as they have in the catfish industry.

Practical diet formulations published in the scientific literature can be used as indicators of reliance on fish meal early in the history of aquaculture feed development. Using catfish diets formulated at Auburn University as an example (Table 1), the drop in reliance on fish meal from 15 percent to 8 percent can be traced over a 20-year period. Discussions with commercial catfish feed formulators indicate that reliance has fallen to an inclusion level of 1 to 5 percent. The overall protein level, however, has remained constant over time. The decrease in fish meal protein has been made up by increases in grain and oilseed proteins.

Table 1. Changes in fish meal content of practical catfish diets

Year	Crude Protein percent	Fish Meal percent	Author
1964	32	15	Hastings
1980	32	10	Lovell
1983	32	8	NRC
1993	32	1 - 5	(Pers. Comm.)

Demand elasticity regarding fish meal prices for poultry feeds has increased to 0.7 in recent years. This means that a 10 percent increase in the price of fish meal would lead to a 7 percent decline in its use. Fish meal prices are affected more by fluctuations in supply and demand than are other animal or plant protein sources (Crowder, 1990). This was demonstrated recently when the fish meal imports during April, May, and June of 1993 were unusually large at 75,117 metric tons, about four times the total for the same period the previous year. The imported meals were being offered at a slightly lower price than domestic meal. This situation reportedly reduced the price of fish meal even more, by $65/ton. This was about 15 percent below normal, and considered by some members of the fish meal industry to be the primary reason why the poultry industry bought more fish meal during that period (NOAA, 1993).

The United States is unsurpassed in its ability to produce cost-competitive, high-quality grain and oilseed products. Exports of these products were expected to total $21.3 billion in FY

1990 (Anon., 1989a). To reduce its dependence on fish meal imports and to increase grain and oilseed exports, the U.S. feeds-processing industry must have substitutes for imported marine protein products. The potential impact of substitution is significant. For example, for every 10 percent of the world market for fish meal replaced by U.S. plant-based protein meal, the trade deficit would decrease by $144 million.

Pollution abatement. The United States, led by the USDA, has been a world leader in the progression of animal agriculture to large-scale, intensive production systems. Research in nutrition and feeds has contributed significantly to the progress made in various types of animal production systems. A common feature of these intensive systems is increasing recognition of environmental concerns and linkages among feed formulation, ingredient utilization, and waste management.

One consequence of intensive animal production, either in aquatic or terrestrial environments, is the output and possible discharge of large quantities of solid waste materials in growout areas. These wastes require considerable management efforts because intensive farm animal production systems have caused acute water quality problems. Recent evidence indicates that agriculture, in general, and animal agriculture, in particular, may be contributing disproportionately to the remaining national water quality problems. In 1991, the USDA Extension Service sponsored the National Livestock, Poultry, and Aquaculture Waste Management Workshop. This was a cooperative effort of the USDA-Extension Service, universities, national organizations, and related agribusinesses and allied industries to address growing concerns regarding disposal of wastes in an environmentally sound manner (Blake et al., 1991).

Debate regarding pollution, national resource conservation, and sustainability issues has transcended the national scale to assume international importance. Environmental issues influenced the General Agreement on Tariffs and Trade (GATT) and the North American Free Trade Agreement (NAFTA), albeit as a tangential concern (Arrow et al., 1996). There is growing concern about sustainability, long-term carrying capacity, ecological resilience, long-term growth, and cost sharing (Fuentes-Quezada, 1996).

A nutritional perspective regarding animal production systems is emerging that is compatible with environmental concerns. H.L. Stillborn, poultry nutritional team leader with Pioneer Hi-Bred International, Inc., introduced the term "EcoNutrition" (1996). Stillborn cited Scott (1991), who suggested that the ultimate aim of nutrition is to increase retention of dietary nutrients, particularly those that may be harmful to the environment if provided in excess. She also cited Summers (1993), Moran and Bushong (1992), Moran et al. (1992), and Moran (1994) to show that diet formulation changes could yield lower nitrogen excretion without impairing weight gain. Similarly, Schwab (1995) stated that feeding high-producing ruminants requires attention to feed quality and diet composition, physical forms of feedstuffs, and feeding strategies. For example, use of "rumen protected" amino acids (i.e., amino acids with protective coatings) prevents microbial degradation of amino acids within the rumen, allowing passage into the small intestine for assimilation. The net results are increased amino acid availability for the animals and reduced nitrogenous waste.

Potential pollution effects for aquaculture species are exacerbated because feeds must be presented to the animals in situ. A complicating factor is that natural productivity, stimulated in large part by feeds, represents a significant component that contributes to the overall nutritional input, particularly in shrimp species. Natural productivity is not a major nutritional factor for cultured fish. Lovell (1994) suggested that high performance, minimum-cost feeds for fish production can be formulated as efficiently as livestock and poultry feeds. Kaushik (1994) stated that the nutritional principals of adequate supply and efficient use of nutrients are common to farm animals and fish production systems, and that both nutritional and feeding strategies can promote maximum nutrient utilization to reduce waste discharges to the environment.

In contrast, shrimp production systems have the most intimate link with biological performance and production conditions. Bacteria and algae in shrimp ponds may enter food webs to influence the nutritional status of the target species, and may also utilize toxic shrimp metabolites to maintain satisfactory environmental conditions (Pruder et al., 1983). More recent evidence has supported the notion that natural productivity is a significant nutritional consideration in intensive shrimp culture (Anderson et al., 1987; Leber and Pruder, 1988; Hunter

et al., 1989; Moss et al., 1992). Balancing pollution effects and the need to stimulate natural productivity are more complicated in shrimp production systems.

It is apparent that animal nutrition research, feeds formulation and ingredient utilization, and environmental issues are now closely linked. Pollution must be minimized and natural resources conserved to accomplish sustainable production of safe and inexpensive food. This involves recognition and acceptance that animal production systems bear these economic, political, and social costs.

Linkage to value-added processing. Multiple benefits can be expected from work designed to seek value-added alternatives to aquatic feeds ingredients. A reduced dependence on fish meal in aquaculture diets means feed producers have alternatives when fish meals increase in cost or decrease in quality. Savings are realized industry-wide. Increasing the scope for formulating diets with alternative ingredients allows the industry to more closely match the nutritional requirements of the target species. This results in lower feeding costs and less pollution. Incorporation of underutilized animal coproducts benefits the animal producers through higher returns and benefits the environment through reduced organic discharges. Ultimately, it is the economic viability of an expanding aquaculture industry that is ensured.

Continuing Needs and Opportunities

A clear opportunity exists for the United States to position itself to fulfill the future marine protein gap. It will take aggressive promotion of agricultural products, processing machinery, and technology, backed up with economic and biological descriptions. The MFC provided a foundation on which future projects of similar intent can be based. There is now evidence to suggest that viable, coproduct and novel ingredients can be applicable to the aquaculture feeds industry through innovative, value-added processing technologies. There is also evidence to indicate that such application carries the economic incentive for ingredient producers to consider the aquaculture industry a viable portion of their business, particularly in light of expanding worldwide marine protein needs. The MFC showed that soybean-based products can legitimately constitute up to 30 percent of a fish diet without hindering performance and decreasing costs. This could translate into an annual increase in soybean demand of around 2

percent. As world trade barriers are reduced and eliminated, the U.S. grain and feeds industries will be well positioned for the exploitation of international markets.

Recommended Future Research Efforts

The MFC provided not only a taste of what can be accomplished in development of new markets for U.S. agribusinesses, but also a solid blueprint for continuing efforts in linking product development in a traditionally terrestrial industry with aquaculture. Clearly, new ingredients and expansion of the species list to include other models should be pursued. The MFC focused on carnivorous species due to the importance of marine protein meal in their diets; however, the bulk of worldwide aquaculture production is based on herbivorous species. Inclusion of herbivorous species would greatly expand the economic potential of targeted ingredients, particularly for export markets such as China where the majority of herbivorous species production is based. In addition, research should also focus on processing methods to improve ingredient digestibility and minimize waste through innovative processing methods. This focus would benefit not only aquaculture but terrestrial animal production systems as well. Pollution abatement will continue to be a key issue in years to come, and this must be addressed through innovative ingredient, feeds processing, and nutritional means. The interaction of ingredients and feeds with the aquatic environment must also be taken into consideration in research designs. This is particularly true of shrimp, which derive a significant portion of their nutritional needs from the pond environment.

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