THE BIOLOGICAL AND ECONOMIC RESPONSES OF GROWING PIGS TO NUTRIENT DENSITY

by

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B.Sc. Agric. (University of Natal, Pietermaritzburg)

Submitted in partial fulfillment of the requirements for the degree of

Master of Science in Agriculture

In the

Discipline of Animal Science and Poultry Science

School of Agriculture and Agribusiness

Faculty of Science and Agriculture

University of Natal Pietermaritzburg

1999

DECLARATION

I hereby declare that the results contained in this thesis are from my own original work and have not been previously submitted by me in respect of a degree at any other University.

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University of Natal
December 1999

ACKNOWLEDGEMENTS

I would sincerely like to express my thanks and appreciation to the following people and organisations;

My supervisor, **Rob Gous**, for his endless time and patience during the course of this degree, I would certainly have not been able to do it without him.

My co-supervisor, **Neil Ferguson**, for his advice and helping hand.

Peter Cherry, for his keen interest in the pig feeder designs and **Gerry Emmans** for his support and inquiring mind.

The author is grateful to **Prof Trevor Morris** for his suggestions and comments.

To the staff at the Ukulinga Research Farm especially **Dudley Tutt**, who helped with all experimentation and supported me through the trials.

To the staff at **Meadow Feeds** and **Epol** for mixing, pelleting and bagging of feeds.

The **technicians** at the **University laboratories**; especially Sue van Malsen, Marianne Hundley, and Debbie Davies, for feed analyses.

The **Foundation for Research and Development** for funding throughout the project.

Lastly to my family **Ronnie, Margie and Peter Nelson** for their financial and emotional support all through the duration of my studies.

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GENERAL INTRODUCTION

In 1974, Fisher and Wilson conducted research into the response of growing chickens to dietary energy concentration. They identified that an economic term to describe the chickens' response was important considering that energy consumption is principally affected when dietary energy concentration is changed. It has been shown that as energy concentration of feed increases, the animals respond by increasing their energy intake, which results in an overconsumption of energy. In order to control the animal's efficiency of utilisation of food, Fisher and Wilson quantified and defined the chickens' responses in order to be able to select the energy concentration that optimises economic returns.

Since such an investigation has only been conducted with broilers (Fisher and Wilson, 1974) and layers (Morris, 1968), this thesis has attempted to quantify the nature of the responses of growing pigs to dietary energy concentration. In doing so it was necessary to conduct an extensive literature review to acquire data on past experiments where diets of differing nutrient density were fed to growing pigs. The objectives of conducting this research were, firstly, to elucidate whether pigs actually have the same response to dietary energy concentration as observed previously in broilers and layers.

The second part of the investigation into the response of pigs to dietary energy concentration involves establishing whether the concept of the optimal foraging theory (OFT) has any role to play in the feeding decisions made by pigs. The optimal foraging theory rationalises an animal's foraging decisions when faced with a range of feed sources and maintains that an animal is by nature an optimal system. Being an optimal system, the animal would attempt to provide itself with all essential nutrients for survival at the least cost. Therefore we would expect to see that pigs would not overconsume energy when faced with an increasing energy concentration in order to minimise work for example, heat produced during the digestion process. This thesis outlines diet selection and the optimal foraging theory as a background to two experiments conducted to test this theory.

A small deviation during this thesis outlines the need for a new feeder design to be used in the choice feeding experiments. Since food intake is the chief factor being measured in these experiments, it was essential to ensure that feed spillage was kept to a minimum or reduced completely

The experiments use choice feeding as a tool to demonstrate whether pigs are capable of choosing an optimal nutrient density and, if so, whether this is similar to the optimum nutrient density calculated by minimising the margin over feed costs. The basic concept therefore is to quantify and discuss the overall differences between the economic optimum nutrient density as calculated from past research, using up to date values of profits and costs, and the biological optimum nutrient densities chosen by the pigs themselves in choice feeding experiments.

CHAPTER 1

DIET SELECTION AS A BACKGROUND TO CHOICE FEEDING SYSTEMS FOR ANIMAL PRODUCTION

1.1 INTRODUCTION

An important but yet unanswered issue facing animal scientists is that of predicting the performance of a given animal in a given state, kept in a given environment. In solving this problem, a perfect description of the needs and desires of animals for food and its surrounding environment is required. In turn, the characteristics of the feeds on offer and the environment within which the animal is kept need to be adequately described, as must the animal itself, before an optimal system can be outlined.

This chapter serves as an outline of the concepts of food preference and diet selection in farm animals. This subject proves to be particularly interesting as animals have limited means by which they can express their nutritional needs. While people can express their preferences in abstract form, animals can only demonstrate which food they prefer by which food they eat, or the ratio of intakes of each food, when given a choice (Forbes and Kyriazakis, 1995). There is now substantial evidence to support the concept that farm animals are quite capable of choosing a balanced diet when faced with a choice of two or more foods, one which has more, and the other less, of an essential nutrient that is required for optimal metabolism. The idea of choice feeding will also be discussed as a means of overcoming the problem of trying to feed animals according to their changing specific requirements.

Experiments have been conducted in the recent past with pigs to determine whether they can recognize both their own nutritional needs and the properties of food which satisfy those needs. This has been termed nutritional wisdom (Rose and Fuller, 1995). This nutritional wisdom ties in with the concept of choice feeding: if animals have sufficient nutritional wisdom, then individuals could select a mixed diet that would accurately meet their requirements. This system of choice feeding could potentially increase the efficiency of food utilization in practical pig production systems, making this method of producing meat more profitable and more efficient in the long run.

1.2 THE UNDERLYING PRINCIPLES

1.2.1 Diet Selection – The Ecological Approach

Animals in the wild are faced with a variety of different foodstuffs from which they have to select a diet most suited to their needs. These foodstuffs are never consistent in their availability or nutritional value, so animals have to vary their diets with the selection on offer to them. In the selection of a diet, animals have to fulfill certain functions besides the satisfaction of their nutritional requirements. They have to avoid the ingestion of harmful substances, as well as exploiting the resources available to them in the most efficient way. For many animals the food supplies are unevenly distributed throughout the environment or may vary seasonally; therefore every animal has to adapt its selection of diet to its particular environment (Rogers and Blundell, 1991).

Competition in the wild plays a role in effective diet selection. In order for the species that exist today to have survived and reproduced as they have done, individuals have had to meet competition from other species and from individuals of the same species (Moss, 1991). This helps to explain why, in the wild, some species are often found to eat a particular food while ignoring others which appear to be nutritionally adequate and which are eaten by closely related members of the same species. An example of this is the difference in diet selection of the black and white rhinoceros; both species of rhino can be found to live in exactly the same environment. Yet the two differ in the composition of their diet; the black rhino is a browser and feeds primarily on leaves of small trees and shrubs, whereas the white rhino is essentially a grazer feeding on grass. In this way, the black and white rhino have survived competition from each other by specializing and becoming more proficient at their foraging strategies for a restricted range of foods and in turn more efficient at digesting them.

Animals have developed a method of selecting the combination of ingredients that best meet their requirements. This ability could be adapted to greater effect by nutritionists to improve the efficiency with which nutrients are supplied to animals.

1.2.2 Animals as Optimizers

Environmental adaptation and competition between animals combined with the concept of survival of the fittest are steps in explaining why some think of animals as optimizers. There has been sufficient time in biological history for these processes to have made the current animals optimal or very close to optimal in their anatomy, physiology and behaviour. Therefore we can expect the animals that we deal with, whether in the wild, or at least initially, in farming practice, to behave optimally (Emmans and Kyriazakis, 1995).

"The animal is assumed to be seeking goals described as achieving maximum rates, as determined by the environment, of carrying out functions such as protein retention in growing animals, egg production in hens and milk production in cows. In order to be successful it needs resources from its environment including those such as energy and amino acids that it can get only from its food. It therefore, given the idea that it is an optimal system, seeks to get these resources from its environment at the rates needed to support the level of performance that the animal seeks" (Emmans and Kyriazakis, 1995).

The operative word in this discussion is 'environment'. The traditional role of agriculture and agricultural research has been to maximize the efficiency of food production. The removal of certain constraints on production has resulted in agriculture advancing progressively further. Man has removed nutritional, environmental and genetic constraints allowing animals today to produce at "unnaturally" high levels. Moss (1991) describes some of the constraints that have been removed: shelter is provided for our domestic animals, contact with natural enemies such as predators, parasites and disease organisms is minimized, as is competition for resources with other species. Seasonal shortages of food are avoided and foraging is greatly simplified. The need to seek out a mate is also largely eliminated.

Domestic animals today live very much more uncomplicated lives than they did centuries ago. As a result, natural selection and survival of the fittest no longer play important roles in their livelihoods. It may now be thought that the optimal animal can no longer be produced. However, the need for these factors has largely been eliminated by selective breeding. Animals can therefore still be expected to be optimizers but this subject remains contentious. Emmans and Kyriazakis (1995) mention that there are some problems with the use of optimality as a starting point for developing quantitative and potentially testable theories. They quote Stephens and Krebs (1986) who point out that "Animals are a mess of competing goals and complex limitations". It is therefore difficult to base predictions on theories of optimality which already involve assumptions about what the goals and limitations (or, possibly, benefits and costs) are in a given case. Application of the theory of optimality has been a source of help in research into diet selection of animal, but the theory of optimality itself is still criticized.

1.2.3 The Optimal Foraging Theory

This theory incorporates much of the last two discussions. It involves the theory that animals are optimizers, and that diet selection takes place in the wild. "Optimal foraging theory (OFT) is an attempt to find out if there are any general rules about what animals feed, where they go to feed and how they search for food. One convenient way to think about these questions is in terms of "decision rules". The animal "decides" to eat this food item and not that one, it decides to hunt here and not there. In this terminology, OFT can be said to be an attempt to understand the decision rules of foraging animals. The rationale of OFT is that these decisions rules have been shaped by natural selection to allow the animal to perform as efficiently as possible, and the aim of a foraging model is to make an informed guess about the meaning of "efficiency" and the constraints that limit efficiency. When these guesses have been built into a model, they can be examined by testing the predictions or assumptions of the model against real data" (Krebs, Stephens and Sutherland, 1983)

Krebs *et al.* (1983) describe an example where many foraging models hypothesize that efficiency can be equated with "net rate of energy intake" and that constraints on maximizing net rate of energy intake include such things as the requirement for certain nutrients.

Later works by Stephens and Krebs (1986) emphasize this net energy concept; "Conventional foraging models maximize the net rate of energy gain while foraging. More energy is assumed to be better, because a forager with more energy will be more likely to meet its metabolic requirements, and it will be able to spend spare energy on important non-feeding activities such as fighting, fleeing and reproducing. Energy can be measured both as a cost (the energy expended in performing a particular behaviour) and as a benefit (the energy gained in performing a particular behaviour). It is thus possible to talk about the net energy gained from performing a particular foraging behaviour."

A common misunderstanding is outlined by Krebs *et al.* (1983), which relates to the theory of optimality. The often-heard statement, "Sheep (or whatever animal is under discussion) do not seem to forage optimally", reflects a misunderstanding of the use of optimality models in biology. These statements cannot be used to test the proposition that one particular hypothesis, for example, maximizing net rate of intake subject to constraints a, b and c, describes the animal's foraging behaviour (Krebs *et al.*, 1983).

"Optimization models are a way of studying the products of selection, namely, the design features of organisms. By formulating design hypotheses in a quantitative and rigorous way, they help circumvent many of the criticisms leveled at the adaptationist approach. There are many criticisms of optimization modeling, including its lack of holism and its lack of attention to phylogenetic constraints. These criticisms amount to reasons why optimization models might be wrong but not why they are bound to be wrong. Design hypotheses are essential features of most biological research, and optimization models seem to be the most explicit and powerful approach to the study of adaptation currently available" (Stephens and Krebs, 1986).

1.2.4 Principles of Diet Selection

Emmans (1991) in his paper on the theory and experimental design of diet selection illustrated a means of describing the choices made by animals for different foods. He used the example of a food consisting of a three component mixture, where the different dimensions are protein, energy and minerals, and the amount of each in a series of foods is indicated by their position in the space. Two components could be represented as a straight line, four by a tetrahedron, etc. (Forbes and Shariatmadari, 1994).

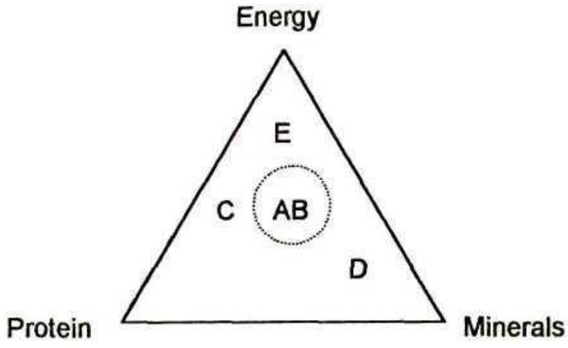

Figure 1.1. *Description of food composition by means of a three component 'space'. The energy, protein and ash contents of a feed can be described by a single point in this space. The ellipse represents the range of foods in which the three components are in balance and the letters A – E are particular foods (Forbes and Shariatmadari, 1994).*

Referring to Figure 1.1, foods A and B are both within the subspace representing adequacy and any mixture of the two would satisfy the animal's requirements. Choice could therefore be random, or according to their hedonic properties interacting with innate or learned preferences for colour, taste or other non-nutritional characteristics. Foods C, D and E lie outside the adequate subspace, but a line between C and D passes through this area so that an appropriate mixture of the two would be adequate; the line between C and E does not pass through the area so there is no mixture of these two which will be adequate. A choice between (A or B) and (C, D and E) requires that A or B are predominantly eaten if requirements are to be met. To test the hypothesis that birds (or any other animal for that matter) make selections from two or more feeds according to their nutrient requirements it is necessary for at least one of the feeds to have a composition outside the adequate subspace (Forbes and Shariatmadari (1994) adapted from Emmans (1991).

1.2.5 *Theories of Diet Selection*

Emmans (1991) elaborated on the principle of diet selection by describing two very simple theories of diet selection. "The first states that the animal, when given two foods, will always eat equal amounts of each and hence, that the composition of the diet will be (0.5A + 0.5B) where A and B are any two foods. The theory applies to all experiments where an animal is given two foods. It has the considerable merit of being simple, explicit and very powerful. Unfortunately it is false. Since it has no general validity it is important to examine carefully experiments where the outcomes are consistent with it." (Emmans, 1991) The second theory that Emmans describes involves the statement that "when an animal is given free and continuous access to two foods it will always show an absolute preference for one over the other. The composition of the diet that it selects will be (1.0A + 0.0B) or (0.0A + 1.0B). Unfortunately this second simple theory is also false." Emmans states that in at least some cases an animal given two foods will eat some of each of them: it appears to behave as if its preference were for some mixture of the two rather than either of the foods alone. He gives the simple example of an animal given a dry food and water, which it would expect to both eat and drink.

A further, more complex theory of diet selection is outlined by Emmans (1991). He distinguishes between two kinds of experiments in which an animal is given free and continuous access to two different foods. In the first kind the two foods are such that some mixture of them is a diet of adequate composition; in the second kind no mixture of the two is of adequate composition.

Where the compositions are such that the animal can choose a diet of adequate composition the theory states that it will. However, there is no statement as to the time-course of the choice. Emmans insists that it is essential that the animal see both foods on offer as foods and will be prepared to eat at least some of each of them. The problem of predicting whether an animal will see a particular material as food is left on one side.

In the second experiment where the compositions of the two foods are such that no mixture of them is of adequate composition, the theory states that the animal will select a mixture of the two of a composition such that its inadequacy is minimized. "The main purpose of the theory is to act as a framework for the design of experiments and to emphasize the minimum requirements for such experiments. To test whether a diet of adequate composition can be selected from a given pair of foods, A and B, it is necessary to give like animals a series of foods made by diluting A and B to varying extents and measuring the performance of the animals on the foods of this dilution series" (Emmans, 1991). Emmans states further that the number of such foods needed may vary with the case but should be at least four, or preferably more. Given such a dilution series the experimental design is made more powerful by giving all the possible two-way choices of the four, or more, foods in the series. With four foods there are six possible two-way choices and five foods ten. Such an experiment was conducted by Bradford and Gous (1991b) and by Kyriazakis and Emmans (1993) in which the pigs given choices as described above, all appeared to choose a diet or mixture of diets, that was most appropriate for them at that time.

1.3 OBSERVATIONS OF DIET SELECTION

1.3.1 The Animal as a Component of the System

"In order to protect the outcomes of an experiment using some theory it is necessary to have descriptions of the system which are sufficient for the theory to be used. Those working in the field of diet selection have, in general, given more attention to describing the foods used than to the animals" (Emmans, 1991). In his discussion about the animal component of the system, Emmans suggests some elements of the description of an animal. It needs to be a means of predicting, for a given animal in a given state, its rates of maintenance, growth and production, and the compositions of growth and production, where neither the diet nor the environment are such that the animal is constrained by them. The diet that the animal needs is then that which it needs to attain that performance; this diet will have a particular composition (Emmans, 1991).

1.3.2 Changing Nutrient Requirements over Time

During the course of an experiment the state of the animal, in the usual case, will be continually changing. If the composition of the diet that it selects is presumed to be some function of its state, as would seem to be reasonable, then the composition of the diet selected will also change with time (Emmans, 1991).

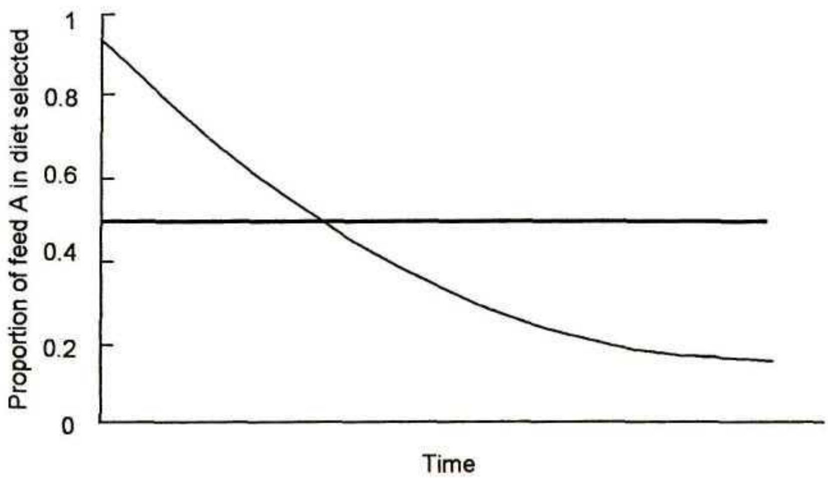

Figure 1.2. Possible changes in diet selection over time (Emmans, 1991).

Emmans explains that *Figure 1.2* shows the possible change in composition of the diet selected by an animal given food A and another one. The composition of the diet selected is expressed as the proportion of A in its total intake. "A picture of the change in diet selection over time, such as that in Figure 1.2, is clearly richer than an observation of the composition of the diet selected at a given time. It would seem sensible to allow animals to have a given choice of foods for long enough for any time effects to be seen" (Emmans, 1991). Bradford and Gous (1991b) designed an experiment to test whether pigs can differentiate between two foods differing in their protein content. The experiment involved the use of a control feed and six choice feeding treatments, where the diets differed only in their protein concentrations. Data were collected during the growth phase (30 to 90 kg) which took an average of 68 days. Isoleucine was suggested to be the limiting amino acid. Estimates of the isoleucine concentrations required by pigs during the growing period were obtained according to a simulation model developed by Ferguson (1989). This model involves predicting changes in food intake, amino acid requirements and body composition over time on the basis of the inherent potential growth rate of pigs. These estimates were then compared to the concentration of isoleucine chosen by the pigs in the experiment. Bradford and Gous (1991b) conclude that, "Considering the close agreement between the concentration of the limiting amino acid selected and that predicted by the model, the latter being based on existing scientific knowledge of the amino acid requirements of growing pigs, it appears that pigs do have the capability of choosing a combination of two foods that match their theoretical amino acid requirements during growth."

The following statement elaborates on Emmans' discussion; "the requirements of growing animals for dietary nutrients are expected to change with time, due to systematic changes in their requirements for maintenance and growth" (Bradford and Gous, 1991b). The highest requirement (expressed as a percentage of protein in the dry matter of the feed) is by the very young animal that is growing at an extremely fast rate relative to its body size. It has a low food intake but requires a large amount of protein and energy per unit feed in order to meet its needs for maximum growth. An older animal which is almost fully mature has a much larger feed intake but requires relatively far less protein and energy per unit feed to meet its requirements (Cuhna, 1977 cited by Bradford, 1988).

1.3.3 Learning as a Means of Differentiating between Foods

Under natural conditions, animals foraging for food are faced with a large number of potential foodstuffs, most of which are nutritionally inadequate. Hughes (1979) describes mechanisms that an animal would require in order to select suitable amounts of each food, if the animal were to ingest an adequate diet. It is difficult to conceive that animals could have a pre-existing recognition system for each nutrient. It is therefore thought that learning must play an important part in diet selection, but it is probably easier to develop specific appetites for some nutrients than others. Hughes (1979) has proposed three patterns of nutrient selection:

1. Predominantly inbuilt, with some "fine tuning" by learning,
2. Predominantly learnt, with genetic predisposition,
3. Inability to learn effectively, perhaps because there is no genetic predisposition.

The first two propositions are presumed to be the most correct, and results of experiments are available that can substantiate these suggestions. Rose (1986) conducted an experiment where a chick was offered a small, bright object, such as a chrome bead. Within a few seconds, it pecked at it spontaneously. If the bead were made to taste unpleasant by dipping it in a bitter but harmless substance such as methyl anthranilate, the chick pecked once, showed its disgust, and avoided pecking a similar but dry bead that was offered any time up to several days later. Bradford (1988) stated that this experiment illustrates that animal can learn to avoid the feedstuffs that are harmful to them. The question of sensory perception can be applied here to attempt to explain this learning phenomenon.

If animals were able to differentiate between the foods on offer by sensory means, no selection would be possible in the first place, no matter how different their nutritional values. Given that such sensory differences exist, it has been thought that the animal may have an innate preference for one food, e.g. because of its sweet taste; or as illustrated in the previous example, an innate dislike for a food because of its unpleasant taste. According to Rogers and Blundell (1991), there are certain taste preferences present at birth that can strongly influence diet selection. He took, as an example, the facial expression of a human newborn. The response to sweet stimuli was a positive facial expression indicating acceptance, while bitter stimuli evoked rejection coupled with negative expressions. Such biases could be considered to be adaptive in that bitter tastes tend to be correlated in nature with the presence of toxins, and sweet tastes will normally signal a ready source of food energy in the form of sugars. This statement reinforces that made by Bradford (1988).

However, nutritional value is not always closely correlated with taste, so the associations that an animal learns between sensory properties and nutritive value, are of much more value to it than is innate preference. Referring back to the example with the chick, conflicting evidence exists that opposes the statement made by Bradford (1988) who suggested that a bitter taste warned animals of a potentially harmful feedstuff. A good example was quoted by Forbes and Kyriazakis (1995): Blair and FitzSimons (1970) included Bitrex, the most bitter substance known to man, in feed which was then fed to pigs. The nutritional value of the food remained constant and the effect that the bitter flavour had on intake was short-lived. There was an initial rejection of the food, but after a few days, normal intakes resumed and long-term intake was not affected. In this case the bitter flavour of the food did not result in rejection, which may, if it had taken place, have been described as a result of the animal disregarding a potentially harmful feedstuff. Thus, there is no need to be concerned about the exact nature of the flavours used to differentiate between two foods as animals soon learn to associate them with the nutrient yields of the food in which the flavours are incorporated and to eat for nutrients and not just for taste (Forbes and Kyriazakis, 1995).

1.3.4 Learning and Memory

Experiments have been conducted in an attempt to evaluate the duration of memory of the nutritive value of food, once it has been learned by the animal. It was found that a sensory property of food which has become associated with a clearly toxic effect of eating the food will evoke long-lasting memories and persistent avoidance (Forbes and Kyriazakis, 1995). Previous work by Garcia *et al.* (1974) cited by Rogers and Blundell (1991) established that animals learn to avoid a food when consumption of that food is paired with illness, in particular nausea and gastrointestinal upset. But, differences in the sensory properties of foods with milder metabolic effects are retained for shorter periods to allow relearning appropriate to changes in the requirement of the animal or changes in the nutritive value of the food (Forbes and Kyriazakis, 1995).

1.3.5 Factors Affecting Intakes of Nutrients

"When a single food is available the intake is determined predominantly by its energy content. However, when two foods are on offer the intake of two nutrients can be controlled independently. Energy and protein are the components of the diet most important in commercial practice, and interest in choice feeding has centered on feeds with protein contents higher and lower than that required for optimum performance." (Forbes and Shariatmadari, 1994). They concluded that selection from two foods is likely to be based on their protein contents, as there is a very wide range of protein contents in readily available feedstuffs compared to the rather small range of energy contents. Protein is an expensive dietary constituent and there is more interest in optimizing its dietary concentration in commercial practice.

All nutrients, and their relative proportions within the feed, influence the voluntary intake of the animal (Williams, 1994). Mraz *et al.* (1957) cited by Williams (1994) have shown that the ratio of nutrients within the diet plays a role in growth responses of animals. An imbalance of the relative proportions of the different nutrients may, through positive feedback, result in an enhanced appetite. This will prevail until either the demand for the nutrient is satisfied, or negative feedback occurs due to the retrograde effects of all the other nutrients which are now consumed in excess.

The bulkiness or density of a feed also affects the intake of nutrients. "Researchers have shown that when eating low nutrient density feeds, or feeds of great bulk, a stage would be reached where further intake, by the animal, would be limited by physical capacity." (Mraz *et al.,* 1956, 1957, Begin, 1961, Cole *et al.*, 1972, cited by Williams, 1994).

"Increasing the environmental temperature to above the thermoneutral range depresses food intake in birds given a single, complete feed" (Forbes *et al.*, 1994). This statement is convincing considering the amount of literature available containing results which agree. Research done on pigs as well as poultry has found environmental temperature to be an important factor affecting nutrient intakes. However, Forbes *et al.* (1991) continue their discussion by saying that if the birds were given a choice between high-protein and low-protein foods it might be expected that protein intake could be maintained while energy intake was reduced to relieve the heat stress. "However, protein metabolism and growth are heat-producing processes and it is difficult to predict the outcome of choice feeding at high temperatures" (Forbes *et al.*, 1991).

1.4 CHOICE FEEDING SYSTEMS

1.4.1 Pigs in Choice Feeding Experiments

There has been a recent revival of interest in the use of choice-feeding systems in which pigs are given the freedom to select from more than one feed. The interest stems from the proposition that pigs recognize both their own nutritional needs and the properties of food which satisfy those needs (Rose and Fuller, 1995). However, there is some conflict among researchers as to whether choice-fed pigs have sufficient nutritional wisdom to ensure that an individual would select a mixed diet that accurately meets it's requirements. If this were true, such individuals could also make daily changes to their nutrient intakes without having to rely solely on changes in their voluntary intakes of a single conventional diet (Rose and Fuller, 1995).

The conflict arises in the difficulty in interpreting the average diet selection of a pen of pigs, as individuals within the pen could select very differently. As demonstrated by Rose and Fuller (1995), the pen mean may be merely an average that may not necessarily represent the choice of an individual. It is obvious that data collected on individually housed pigs are more valuable in examining the extent of their abilities to select diets.

Work done in the subject of choice-feeding has resulted in much convincing evidence that pigs are able to distinguish between two feeds which differ in protein or amino acid concentration (Fairley, Rose and Fuller, 1993, cited by Rose and Fuller, 1995). Results of experiments discussed by Rose and Fuller (1995) lead to the same general conclusion that pigs can certainly discriminate between diets which differ only in the concentration of an amino acid, often preferring feeds that avoided a deficiency of that amino acid.

1.4.2 Selection of Feeds to Satisfy Nutrient Requirements

Kyriazakis *et al.* (1990) state that, "It is concluded that the pigs selected their diet, the composition of which changed systematically as they grew, in a directed manner. The quantity eaten and the composition of the diet selected appeared to reflect the pigs' requirements for maintenance, growth and fattening."

On the same subject, Bradford and Gous (1991b) state that, "...it appears that pigs do have the capability of choosing a combination of two foods that match their theoretical amino acid requirements during growth. The choice made by pigs appeared to be closely related to the first-limiting amino acid in the two foods on offer, which is a central proposal in the theory of food intake regulation proposed by Emmans and Fisher (1986)."

The second statement by Bradford and Gous (1991b) tends to relate to the statement made by Rose and Fuller (1995) mentioned earlier. Rose states that the "pigs' feed preferences seem to have been dominated by the avoidance of a lysine deficiency". In this case, lysine may have been the first-limiting nutrient, and so their opinion agrees with that of Bradford and Gous (1991b).

There is still some debate as to whether pigs have the ability to choose a perfect diet. However, even Rose and Fuller (1995) make the statement that, "it is still possible that a practical pig production system could use a choice-feeding system."

1.4.3 Equipment in Choice Feeding Systems

A choice-feeding system imposes extra costs in feeding equipment. Two feed storage bins rather than one would be needed and two feed troughs would be needed in each pen even though the pen size might only justify one. A sophisticated feed delivery system would be needed to ensure that the correct feed was dropped into the correct feed hopper. These extra feeding costs are small relative to the total cost of feed in a pig growing and finishing unit. However, a choice-feeding system would also need additional management. Choice-feeding must lead to a significant improvement in production efficiency and must be cost-effective if pig farmers are to be persuaded to adopt it (Rose and Fuller, 1995).

1.4.4 Selection of Feeds

Because energy and protein are the two most costly components of a practical pig feed, a choice-feeding system that would allow growing or finishing pigs to choose an appropriate energy:protein ratio would therefore have most practical benefit (Rose and Fuller, 1995). "It is difficult to supply to all pigs at all times the optimum ratio of energy:protein in a practical diet. The optimum ratio changes continuously as pigs grow and is also affected by such environmental factors as ambient temperature. The genetic potential and sex of the pigs can also affect the energy:protein ratio they require." (Rose and Fuller, 1995)

Bradford and Gous (1991b) and Rose and Fuller (1995) suggest that a choice of two feeds that have the same energy concentration but differ in protein concentration would allow pigs to select between two energy:protein ratios. Both feeds would contain the correct concentrations of all other nutrients required for growth.

After examining seven experiments in the literature in which this type of choice-feeding system has been compared directly with a single feed system, Rose and Fuller (1995) came to the conclusion that, "there is no evidence that there is any improvement in growth or efficiency in pigs given a choice between a high- and a low-protein feed. The increased capital cost of implementing a choice-feeding system is therefore unlikely to be justified by any improvement in pig performance."

Another selection of feeds to offer could be between a cereal and a balancer feed, as cereals account for more than 50% of the cost of a complete pig feed (Rose and Fuller, 1995). Rose and Fuller (1995) describe choice-feeding regimens in which pigs have been given a choice of two feeds based on a complete balanced diet, the cereal component and a balancer feed that consists of all the other components of a balanced diet. The balancer feed generally contains protein concentrates, minerals, essential fatty acids, vitamins and perhaps also some cereal. This combination of feeds allows the pigs to select the energy:protein ratio of their diet. The vitamin and mineral concentrations in the balancer feed can be adjusted to provide optimum intakes of these nutrients. The results of such an experiment are shown in Table 1.1.

Table 1.1. The productive performance and economic comparison of growing pigs given either a complete single feed or two choice-feeding regimens for 12 weeks (Rose, 1994, unpublished, cited by Rose and Fuller, 1995).

Treatments	Live weight gain (kg/pig)	Feed intake (kg/pig)	Proportion of wheat selected (kg/kg)	Feed conversion ratio (kg/kg)	Feed cost (Pounds/ pig)	Feed cost per kg live weight gain (pence/pig)
Complete single feed	69.0	155.9		2.266	28.68	41.6
Choice feeding treatments						
Balancer: ground wheat	61.4	161.8	0.472	2.635	26.79	43.6
Balancer: whole grain Wheat	55.8	160.8	0.621	2.879	25.75	46.1
SEM (9 df)	2.33	9.11	0.087	0.1137		

From the results obtained from this experiment, Rose and Fuller (1995) concluded that, "choice-feeding systems that offer a cereal with a balancer feed have the potential to reduce feed costs. However, growth rates and feed conversion efficiencies tend to be reduced and so the cost of producing each kg of live weight gain may be greater."

In conclusion, Braude (1965) cited by Rose *et al.* (1995) reviewed the use of complete single feeds and choice-feeding and concluded that the latter is doomed when very high efficient performance is aimed at. Rose *et al.* (1995), on the same subject, state that, "the evidence produced since that time does not seem to justify any change to that opinion."

1.5 DISCUSSION

In animal production systems an attempt has been made to imitate the natural environment in which animals would be found in the wild. This environment describes their housing, their feed, as well as conditions such as temperature and space. As the world's population grows and the demand for protein as food for the masses increases, these systems are becoming more and more geared towards producing this food at the most efficient and economical level. Bradford and Gous (1991b) made an optimistic statement about choice-feeding systems in the pig industry, "In commercial operations this method of supplying the different protein needs of individuals, each having a different potential growth and maintenance requirement, appears to have merit. The system would be simple to implement, would be cost-effective and would result in leaner carcasses than would be the case when pigs are grown on a single-food system during the period 25 to 90 kg live weight."

Studies in animal nutrition have increased the efficiency with which animals can be produced for food, but there is still room for improvement; for nutrient requirements, nutrient contents in feedstuffs, feed delivery systems, nutrient x environment interactions and other aspects of nutrition to be measured, or studied, in greater detail. Choice feeding, based on the optimal foraging theory, is a valuable and useful technique that may be used in such studies. Future research could profitably make use of this tool in further elucidating nutrient requirements of animals, and even testing whether new feedstuffs are acceptable to animals or not. In this thesis, use is made of choice feeding as a tool to compare the optimum nutrient density of pig feeds as perceived by the pigs themselves, versus that based on economic principles.

CHAPTER 2

THE DESIGN OF A NEW PIG FEEDER TO MINIMIZE FEED WASTAGE

2.1 INTRODUCTION

When conducting animal nutrition experiments, accurate measurements of food intake are crucial. In the pig experiments carried out at Ukulinga Research Farm, food intake is always recorded as a means of calculating the efficiency of conversion of feed into body weight gain. Unfortunately, episodes of feed spillage by animals have been experienced in these facilities, which have reduced the confidence with which we can report results. In recording the amount of food eaten, little or no account of spillage has been taken, and where effort has been made to do so, the readings are merely subjective observations which would certainly contribute to error in the long term.

In order to overcome the problem of spillage, two options were considered; the first was to create a means of measuring the amount of food spilled by being able to collect and weigh all of the spilled food. The second, presumed to be more accurate in the long term, was to eliminate spillage by changing the design of the feeder. A 'prevention is better than cure' attitude was therefore adopted. The problem was identified, defined, and solutions were proposed taking account of constraints. These were tested and after measuring their effectiveness, modifications were made until the best solution was found.

2.2 SCENARIO

The ideal feeder for minimising or eliminating feed spillage had to be defined with the following constraints:

1. It should be relatively easy and inexpensive to modify – 144 feeders were to be altered, and expenditure had to be kept to a minimum.

2. The feeder had to work well irrespective of the age of the pig.

3. Feed had to be available *ad libitum* but only a small amount of feed should be available at the base of the feeder.

4. The feeder should be able to handle both mash and pelleted feeds.

2.3 SOLUTIONS

2.3.1 Initial feeder design

Figure 2.1 is a diagrammatic representation of the initial feeder design. The adjustable front panel was not effective against preventing substantial amounts of food from flowing into the feed trough, potentiating spillage.

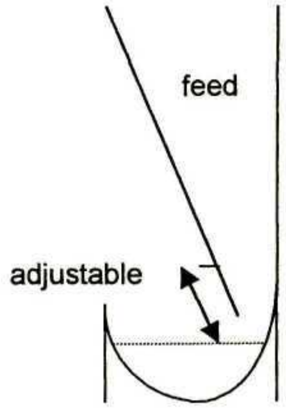

Figure 2.1. The initial design of the feeder at the Ukulinga Research Farm piggery.

2.3.2 *Solution 1*

The front panel was secured on the side panel at different points on an arc as indicated in Figure 2.2. The modification attempted to reduce the level of the feed in the base of the trough.

Four feeders were altered according to the specifications in Figure 2.2. The front panel of the feeder was cut free and able to pivot from the top. Three holes were made on both sides of the feeder in order to alter the angle of the front panel, changing the level of feed and space available for the pig's head when feeding. A metal bar with a handle was inserted through the holes to secure the panel. The adjustable plate at the bottom of the panel was retained but made easier to adjust by attaching hooks at the top instead of having to twist the bar to adjust the length.

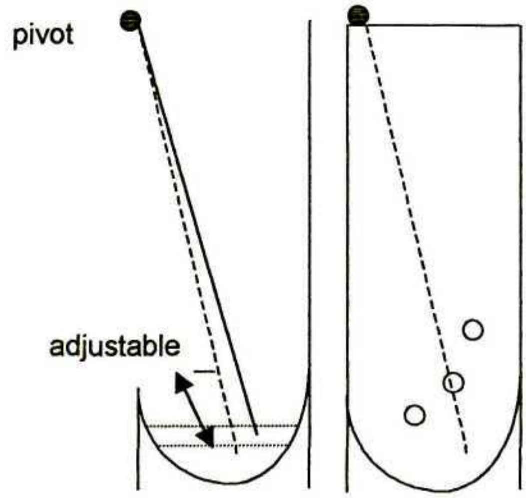

Figure 2.2. Solution 1: An attempt to reduce the level of feed available.

2.3.3 *Solution 2*

The second solution to be put into practice involved the addition of a metal lip on the front of the trough. This modification, as shown in Figure 2.3, was an attempt to prevent the pig from scraping the feed from the trough with its forelegs. This design could have been used as an addition to the solution in Figure 2.2, but would not solve the problem of restricting the amount of feed available in the base of the trough.

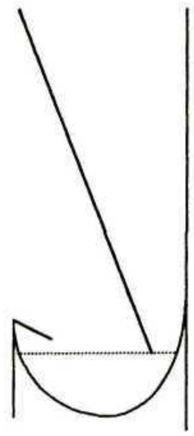

Figure 2.3. *Solution 2: The addition of a lip to prevent the pig from scraping out the feed.*

2.3.4 Solution 3

One feeder was adjusted as in Figure 2.2, but the metal plate was welded against the front panel and reinforced with two metal plates on either side to prevent the weight of the food from bending the plate forward. The length of the panel was such that the widest angle had the smallest gap at the bottom to allow for the passage of food. The holes to secure the angle of the front panel were moved further back.

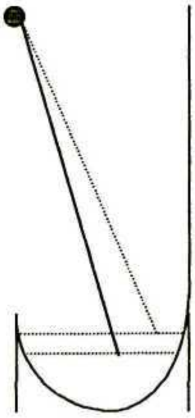

Figure 2.4. *Solution 3: Reinforcement addition to Solution 1 (Figure 2.2).*

2.3.5 *Solution 4*

The front panel of one feeder was cut away from the sides and welded into place further back along the sides of the feeder, as shown in Figure 2.5. The bottom plate was also welded into place below the front panel leaving a gap only high enough (±2.5cm) to allow movement of a chain to facilitate flow of the feed. This design could therefore eliminate the problem of having to adjust the feeder against the force of a full bin of feed. A chain was attached at the back of the base of the feeder, extending through the gap through which the feed was to flow. When this chain was moved, it caused the feed to start trickling down. This feeder was tested with a medium sized pig (50kg) and with two 15kg weaners.

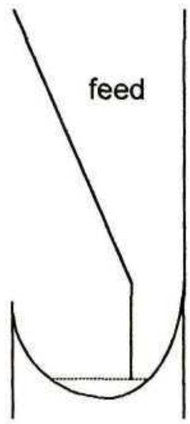

Figure 2.5. Solution 4: Secure design requiring no adjustment.

2.4 TESTING THE DESIGNS

Animals and housing

Four 15kg weaners (2 gilts and 2 boars) were obtained from a farmer in Lion's River and placed in individual pens at the pig research facility.

Feed

A high energy and high protein feed was offered to the pigs, which they seemed to enjoy. They were given *ad libitum* access to this feed.

Observations

Feeding habits, feed spillage and general behaviour were observed.

2.5 EVALUATION OF THE DESIGNS

2.5.1 Solution 1

1. A potential problem with this design was that when the feeder was secured at the first peg, there was not enough space available for a grown pig weighing 90kg to feed comfortably.

2. Only once the four feeders were modified and feed placed into the bins was it realized how difficult it was to change the position of the front panel. In the experimental situation, the bins would not be less than approximately a third full and, inevitably, the front panel would have to be moved further back as the pigs grew larger. The weight of a full bin of feed on this panel was too great to allow a movement of even a few centimeters.

3. The adjustable plate at the bottom of the front panel was not strong enough to withhold the force of the feed and consequently bent outwards slightly.

4. The hooks to secure the plate at a specific height were useless, as the pigs learned to lift the plate with their snouts when eating from the feeder, thus letting copious amounts of feed through.

5. The metal bars protruding from the side proved to be a source of amusement to the animals and not one was happy until the bars had been removed!

6. No spillage of feed was observed at all, even though the small pigs would often put one or both feet into the feeder at eating times. The small lip on the current feeder served to prevent the pigs from scraping food out.

2.5.2 Solution 2

1. A potential problem that was identified was that feed might collect under the lip, turn sour and begin to rot. In this case, the pig may reject the feed on offer altogether.

2. Cleaning of bins once experimentation had been completed posed an additional problem. The feed that collected under the lip would be time consuming and problematic to remove.

3. The potential problems of this design outweighed the possible benefits and therefore testing of this design was abandoned.

2.5.3 Solution 3

1. An advantage of this design was that the need for adjustment on the front panel was removed, thus making the alteration of the feeder that much easier.

2. No spillage was noted, but the problem of needing to adjust as the pigs increased in size was not removed. The problem of having to force the feed back to move the front plate remained.

3. The amount of feed presented to the pig was much less than in the case of the other designs, as the plate now provided a solid restraint to feed pouring through into the trough.

2.5.4 Solution 4

1. The major advantages to this design were that no adjustments were needed during the growth period of the pig, and that pigs had to work for their food, which satisfies their rooting instinct.

2. One problem that was encountered was that small pigs tended to put their front legs into the feeder to get to the back of the feeder where fresh food was available. From the observations made it seemed impossible for small pigs to keep both feet on the ground while reaching the food at the back of the trough, as the front lip of the trough pushed against their throats making it difficult for them to swallow. The small pigs would work at the gap by scraping with their feet and moving the chain with their mouths.

3. During the time these pigs were feeding from this design, no problems were noted.

2.6 INFORMAL CHOICE FEEDING TRIAL

The feeder design outlined in Solution 4 was tested further in an informal choice feeding trial. Due to the nature of the feed on offer (high protein and energy) there did not seem to be any temptation for the pigs to remove the feed from the bin as they might be expected to do if they had to select for nutrients. To test the feeder design when a low density feed was on offer, the high density feed was diluted in the ratio 2:1 with finely milled sawdust. The possibility was that a lower nutrient density feed would tempt the pigs in to removing this feed from the feed bin. A trial period of two days with the high density feed on its own, and three days with the diluted feed alone, was used in order to accustom the pigs to both feeds on offer. Thereafter both feeds were offered simultaneously giving the animals a choice between the two.

Results

1. When the diluted feed was the only food on offer, no evidence of spillage was noted, but a substantial amount of feed and sawdust had collected in the bottom of the trough. This was probably a result of the pigs sifting through the diluted feed to obtain the amount of essential nutrients needed. Had the sawdust been finer, or if the feed had been pelleted, the pigs would have found it more difficult to sift through the mixture. Nevertheless, the level of feed in the trough remained at a lower level than the original feed trough would have allowed.

2. After three days with a choice of the two feeds, it was noted that the pigs continued to eat from the feeder containing the diluted feed as well as from the feeder containing their normal feed. This conclusion was drawn from visual assessment of the amount of food in the bin over the days, and not actual measurements.

3. No spillage was observed from either feed bin during the time span of this informal feeding trial.

4. In subsequent experimentation at the Ukulinga Research Farm piggery, the feeders have proved to reduce the amount of spillage dramatically.

2.7 CONCLUSION

By applying a problem-solving approach to the problem of feed spillage with the original feeder design, a new feeder was designed that eliminated feed wastage altogether. In essence, the level of feed in the trough was lowered, and this had the effect of making it more difficult for the pig to spill feed on the floor. During the time span of this trial, the feeder was tested on both small and medium-sized pigs (15-45 kg). The resulting observation of feed spillage indicates that the new design can be considered to have a significant effect on reducing the amount of feed that is wasted. One problem that was encountered during experimentation, and which has not yet been solved, was that the feed bins were fouled by the pigs, resulting in the feed flow being restricted by clogging and whereafter many of the animals would not consume the fouled food. A possible solution to this problem could be to adapt the feeder designed by Baxter (1989) as shown in Figure 2.6. Extending the sides of the feeder out at rump height for the weaners, may make fouling of the feed more difficult.

The problem-solving approach has been shown to be effective in overcoming difficulties encountered in the accurate measurement of food intake in growing pigs. Applying the concept of continual improvement would lead to an even more efficient design in the future. However, it was felt that solution 4 would give sufficiently accurate measurements of food intake for the purposes of the subsequent trials, and this design was therefore adopted and applied to all the feeders in the facility.

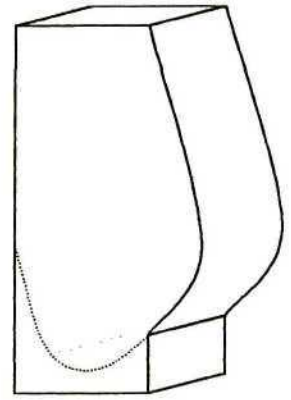

Figure 2.6. A future consideration to reduce fouling of the feed.

CHAPTER 3

DETERMINATION OF RESPONSES OF GROWING PIGS TO CHANGING DIETARY ENERGY CONCENTRATION

3.1 ABSTRACT

The responses in growing pigs to balanced diets at different dietary energy levels are estimated from published data after recalculation of digestible energy (DE) levels using standard tables. The purpose of this paper was to apply the general responses to formulate feeds to optimize profit margins. Although responses in live weight gain (ADG), food intake (FI), digestible energy intake (DEI) and food conversion efficiency (FCE) are calculated, it was not to quantify the absolute relationship between these variables and dietary energy levels. Linear regressions of ADG, FI, DEI and FCE on DE accounted for 82, 97, 97 and 93%, respectively, of the variation amongst the 15 estimates of the responses. Most of this variation was accounted for by difference amongst the constant term of the various experiments, which implies small differences amongst the slopes. The genotype of pig and live weight were found to be important in influencing the rate of response in some characteristics. The optimum nutrient density of the feed chosen will depend upon the efficiency of feed utilization, the cost of the feed and the income derived from the end product. The energy level at which margin over feed costs are maximized will be the optimum nutrient density.

Keywords: energy, nutrient density, pigs, profits

3.2 INTRODUCTION

It has been shown that the response of *ad libitum* fed growing pigs to dietary energy concentration is mainly in food or energy consumption, which has consequences for the efficiency of food utilisation and carcass quality (Owen and Ridgman, 1968; Campbell and Taverner, 1986; Kyriazakis and Emmans, 1995). Rate of body weight gain is affected to a much lesser extent. To choose an optimal dietary energy concentration, one first needs to define the biological responses of pigs offered diets formulated to various energy levels and then combine the results with the costs of formulation and the value of the outputs, all of which vary with time and locality. Fisher and Wilson (1974) conducted a survey of data for chickens and so determined their response to dietary energy and what factors would affect that response. This paper will conduct a similar investigation in growing pigs from 10 to 90 kg live weight. To quantify the nature of the responses of the growing pig to dietary energy concentration data from publications that meet certain criteria were acquired and analyzed before applying monetary values to the feed costs and animal outputs.

The objective of this paper was to apply the general response trends to practical formulation of diets to optimize profit margins rather than to relate absolute levels of ADG, FI, DEI and FCE to dietary energy concentrations.

3.3 METHOD

Firstly it was necessary to determine what criteria would be used to select data. Once the data from suitable experiments had been obtained they were used to quantify the responses to dietary energy levels and to what extent factors like genotype, live weight, sex and housing would affect the response. Lastly economic responses were derived, from which optimum dietary energy concentrations could be determined for application in the formulation of practical pig diets.

3.3.1 Selection of Data

The following criteria were used to select the appropriate experiments:

1. Nutrient and ingredient composition of the diets must be provided with sufficient detail to allow recalculation of dietary energy levels.
2. Diets must have a constant energy:protein or energy:amino acid ratio.
3. Animals must have had free and continuous access to feed.
4. Growth and feed intake results must be available in a form that allows additional calculations to be made.

To ensure more accurate estimates of dietary energy levels it was necessary to recalculate the energy concentrations from the ingredient composition of the diets. The publications used in this paper are shown in Table 3.1. Results from ten experiments were included to provide a total of 17 response lines (or curves) with the number of digestible energy (DE) levels tested in each trial varying from 2 to 6 giving a total of 66 observations per response variable. The 66 observations were derived from the number of responses x DE levels over all experiments (Table 3.1). Other data sets were rejected because animals were not fed *ad libitum* (Lodge *et al.*, 1972; Lawrence, 1977; Pike *et al.*, 1984) or because energy:protein ratios were not constant across diets (Baird *et al.*, 1975).

Table 3.1. Summary of the response information used from the literature.

Reference	Number of responses	Energy levels per response
Ball and Aherne (1987)	1	2
Campbell *et al* (1975) Expt 1	1	4
Expt 2	1	5
Campbell and Taverner (1986)	1	5
Kyriazakis and Emmans (1995)	1	5
O'Grady (1978)	1	2
O'Grady and Bowland (1972)	2	4
Owen and Ridgman (1967)	3	6
Owen and Ridgman (1968)	5	3
Patterson (1985)	1	2

3.3.2 Determination of Biological Responses

The four production variables considered were average daily live weight gains (ADG), feed intake (FI), digestible energy intake (DEI) and feed conversion efficiency (FCE). Data for these variables were obtained from the published results. To determine the effects of each trial separately and the effects of descriptive factors a linear regression model using "dummy" variables was fitted using the Least Squares method in Minitab (1994). Dummy variables were used to determine whether there was a common intercept and/or slope between experiments and various descriptive factors were applicable.

The following model was used to fit the data:

$$Y = a_0 + b_0X_0 + a_1 + b_1X_1 + ... + a_i + b_iX_i + e \quad (1)$$

where Y = response variable

a_0 = constant or intercept term for the "first" experiment

b_0 = slope value for the "first" experiment

X_0 = Digestible Energy concentration of "first" experiment

$a_{1..i}$ = effect of an additional experiment or descriptive factor ($X_{1..i}$) on a_0 (intercept)

$b_{1..i}$ = effect of an additional experiment or descriptive factor ($X_{1..i}$) on b_0 (slope)

$X_{1..i}$ = Digestible Energy concentration of additional experiment or, either 0 or 1 for a descriptive factor

e = residual error

Factors that had some commonality between experiments were breed type, live weight, sex and housing arrangements. When considering whether these factors had any significant effect on the various responses, regression coefficients were compared by t-test. Because there has been a marked improvement, due to genetic selection, in growth rate and carcass quality it was appropriate to divide breed type into two categories according to year of publication. Results obtained prior to 1980 reflected a slower growing, fatter type of pig (Fat) while after 1980 it was assumed that the pigs grew faster and were leaner (Lean). There were insufficient data to justify more than two categories. In terms of live weight, five levels were defined: 10 - 30 kg, 30 - 60 kg, 60 - 90 kg, > 90 kg and between 10 and 90 kg. Unfortunately there was only sufficient replication in the available data in the first three weight categories and therefore only these were considered separately in the analyses. The sex variable comprised of males only and males and females together: there were no suitable data for females only. Housing defined the effects of individual versus group pens.

After initially including the data from the two experiments of Campbell *et al.* (1975) it was found that these data had a strong negative influence on the regression responses such that their inclusion substantially reduced the goodness of fit of the model. The reason for the negative effect lay in the young age (3 to 8 weeks) and low live weight range (5.4 to 20 kg) from which the data were obtained with the result that values for ADG, FI and DEI were considerably lower than any of the other data used in this paper. In an attempt to remove as much error variation as possible both the experiments of Campbell *et al.* (1975) were excluded from further analyses.

3.3.3 Determination of Economic Responses

To apply the responses in FI, ADG and FCE to energy concentrations it is necessary to attach monetary values to both input costs and prices obtained for the end product. From the estimates of biological responses to DE it is possible to determine the economic response expressed in terms of margin over feed costs. This step requires estimates of energy and amino acid requirements over various stages of growth and fattening in order to formulate feeds and obtain a cost per feed. For simplicity and comparability with the literature the growth phase of the pig was divided into three weight categories (10-30 kg, 30-60 kg and 60-90 kg live weight) each with their own nutrient requirements. Diets were formulated on the basis that lysine was the most limiting amino acid with the remaining essential amino acids balanced according to the ideal ratio of Wang and Fuller (1989). Lysine:energy ratios for the three phases of 0.75, 0.65 and 0.55 g lysine/ MJ DE respectively, were used in the formulation of rations. These ratios were based on current practice in South Africa. However, to compare with what is more appropriate to achieve maximum potential lean tissue growth during the respective live weight ranges of current genotypes (Whittemore,1993), an additional set of ratios of 0.80, 0.75 and 0.70 g lysine/ MJ DE were also tested. Table 3.2 provides details of the cost of the respective diets.

Table 3.2. The cost of rations (R/ton) based on different dietary energy concentrations and nutrient densities (lysine:digestible energy).

	g Lysine/ MJ DE				
DE (MJ/kg)	0.55	0.65	0.70	0.75	0.80
10.0	676	717	736	767	796
10.5	700	740	765	790	825
11.0	732	776	799	831	860
11.5	772	821	845	869	907
12.0	822	871	897	924	963
12.5	875	924	958	997	1035
13.0	929	983	1021	1069	1109
13.5	985	1050	1102	1135	1173
14.0	1046	1122	1180	1206	1256
14.5	1130	1195	1265	1288	1339

Income was derived from the marketing of pigs at 90 kg live weight or 67 kg slaughter weight assuming a 74% dressing percentage. An average carcass price of 750 c/kg was used, which is close to the average price/kg for the third quarter of 1997 of 765 c/kg (Livestock and Meat Statistics, 1997).

Margin over feed costs was used to determine the optimum nutrient density and results were expressed as a proportion of the margin over feed costs at 10 MJ/kg DE. The optimum nutrient density is determined from the maximum margin over feed costs per batch of pigs. This would be the concentration of dietary energy and amino acids that would provide the maximum economic returns rather than maximum biological performance.

Factors that were found to significantly affect the responses to DE would also be incorporated into the determination of the optimum nutrient density by separating their effects on the response to DE.

3.4 RESULTS AND DISCUSSION

To check whether the growth responses to DE were linear, a quadratic term was added to the linear model described in Equation 1. The results showed only the linear responses were significant ($P < 0.05$) with no significant quadratic effects ($P > 0.05$). It is assumed in this paper therefore that the growth responses to DE are linear.

Fitting data to the model defined in Equation 1 accounted for 82 - 90 percent of the variation in all responses to DE with the constant terms for trials accounting for most of the variation between experiments. Although there were no significant differences in slopes between experiments the inclusion of other factors did result in significantly different slopes. When considering the effects of live weight, sex, genotype and housing on the responses to DE after fitting constants for the different experiments only live weight and genotype were found to have any significant effect. Therefore the remainder of the discussion will be confined to the effects of these two variables. The influence of genotype and live weight will be discussed separately in each of the respective responses. As this paper is only concerned with the nature of the responses and not absolute values for each response variable, and as responses by definition involve a rate of change, particular attention will be given to the regression coefficients and not the constant terms. Table 3.3 and 3.4 provide summaries of the regression coefficients and their significance before and after including the effect of genotype and live weight. Because of the low number of degrees of freedom a significance level of $P < 0.10$ was considered as note worthy and given as a significant response (‡).

Table 3.3. A summary of the regression slopes (b_1) and their standard errors (s.e.) for feed intake (FI) (kg/d), DE intake (DEI) (MJ/d), average daily live weight gains (kg/d) and feed efficiency (FCE) (g gain/kg food) regressed on DE (MJ/kg) and the level of significance (P) and variation accounted for by the linear model (R^2) before considering the effects of live weight and genotype.

Response	b_1	s.e.	P	R^2
FI	-0.0567	0.0184	**	96.9
DEI	1.687	0.204	***	97.1
ADG	0.0375	0.0066	***	81.7
FCE	29.687	4.625	***	92.6

For P: ** = < 0.01; *** = < 0.001

Table 3.4. A summary of the regression slopes (b_1) and their standard errors (s.e.) for feed intake (FI) (kg/d), DE intake (DEI) (MJ/d), average daily live weight gains (kg/d) and feed efficiency (FCE) (g gain/kg food) regressed on DE (MJ/kg) and the level of significance (P) and variation accounted for by the linear model (R^2) after considering the effects of live weight and genotype.

		10 – 30 kg		30 – 60 kg		60 - 90 kg		> 90 kg		10 – 90 kg		R^2
Response	Genotype	b_1	P¶	b_1	P¶	B_1	P¶	b_1	P¶	b_1	P¶	
FI	Fat	-0.051	NS	0.032	NS	-0.089	NS	-0.170	**	-0.064	NS	97.8
	S.e.	0.106		0.075		0.071		0.077		0.079		
	Lean	0.009	NS	-0.043	NS	nd		nd		nd		
	s.e.	0.077		0.064								
DEI	Fat	0.557	NS	2.361	**	1.901	*	1.251	NS	1.955	*	97.5
	S.e.	1.297		0.916		0.875		0.942		0.974		
	Lean	1.048	NS	1.547	‡	nd		nd		nd		
	s.e.	0.942		0.784								
ADG	Fat	0.0169	NS	0.0356	NS	0.0255	NS	0.0066	NS	0.0229	NS	88.9
	S.e.	0.0348		0.0246		0.0235		0.0253		0.0261		
	Lean	0.0941	***	0.0728	***	nd		nd		nd		
	s.e.	0.0253		0.0210								
FCE	Fat	34.95	**	12.41	NS	16.17	‡	14.74	NS	14.66	NS	98.7
	S.e.	12.99		9.17		8.76		9.43		9.75		
	Lean	94.98	***	43.23	***	nd		nd		nd		
	s.e.	9.43		7.85								

¶ P: NS = Not significant; ‡ = < 0.10; * = < 0.05; ** = < 0.01; *** = < 0.001

nd = no data available

Classification of the responses into the various genotype and live weight categories was not equal. In the Fat strain of pig there were 2, 3, 3, 2 and 1 responses for the 10-30 kg, 30-60 kg, 60-90 kg, >90 kg and 10-90 kg subgroups respectively, and for the Lean strain there were only 3 and 1 responses for the 10-30 kg and 30-60 kg groups respectively.

The initial analyses of the 61 observations from 15 responses (excluding Campbell *et al.*, 1975) based on Equation 1 accounted for most of the variation through fitting different constants and a single slope for the different experiments. Further slight improvements in the models for DEI, ADG and FCE could be made by adjusting the slope value to take into account the effects of genotype and live weight (Table 3.4). From an economic point of view the response in FCE was of greatest importance as it allowed for the estimation of feed costs without requiring an estimate of days to market.

3.4.1 Response in Food Consumption to DE

Without considering the effect of genotype, live weight or anything else most of the variation was accounted for after fitting the constant term for the different experiments (R^2 = 96.9%). There were no significant differences in slopes between experiments and therefore it can be assumed that the responses in FI to DE share a single slope value (-0.0567 kg d^{-1} /MJ DE kg^{-1}). The regression coefficient was significantly different ($P < 0.01$) from zero. Figure 3.1 illustrates the relationship between FI and DE. Genotype and live weight had no effect in improving the accuracy of the response within the weight categories 10-30, 30-60 and 60-90 kg.

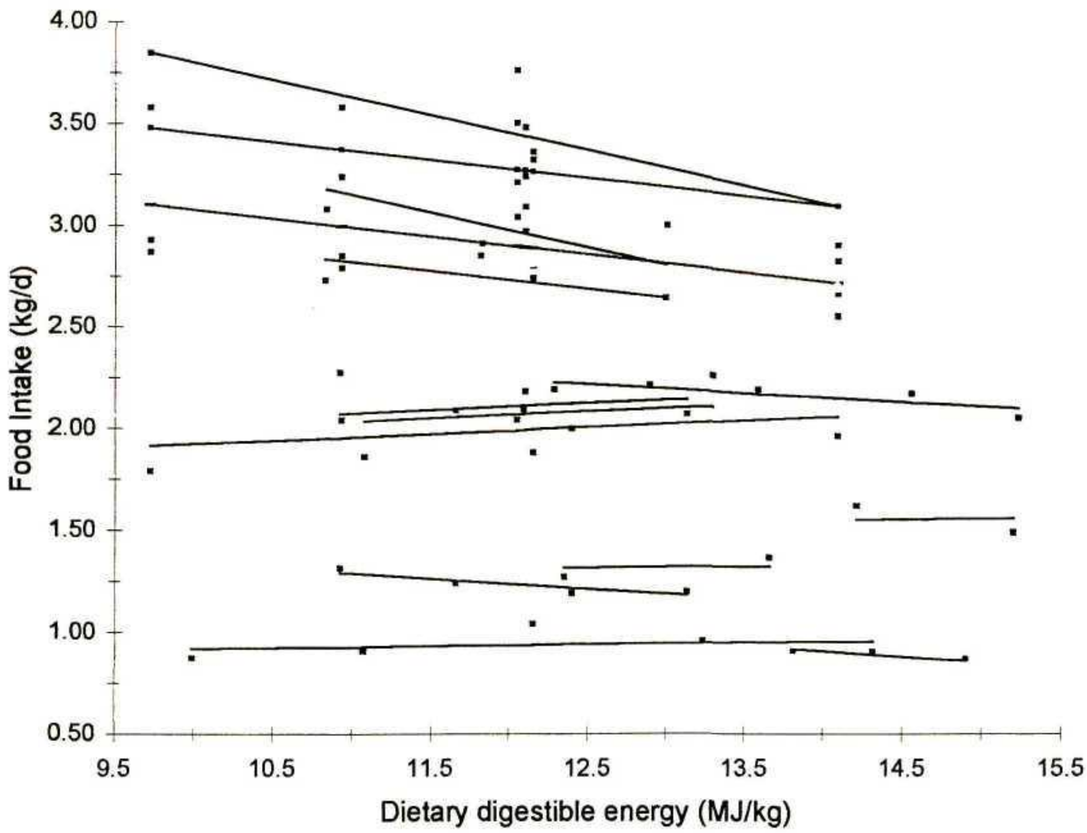

Figure 3.1. Relationship between daily food intake and dietary digestible energy. (—) Fitted values from regression model incorporating live weight and genotype effects; (■) published data.

3.4.2 Response in Energy Intake to DE

Energy intake increased with increasing DE content at a rate of 1.687 MJ/d per MJ DE /kg (Figure 3.2). This rate was significantly different from zero and therefore of practical importance when formulating feeds because it allows for the optimum balance to be attained between feed costs and energy intake. However, the response in energy intake was affected by live weight and genotype such that for Fat pigs greater than 30 kg live weight the rate at which energy intake increases with increasing dietary DE level is greater than for Lean type pigs (Table 3.4).

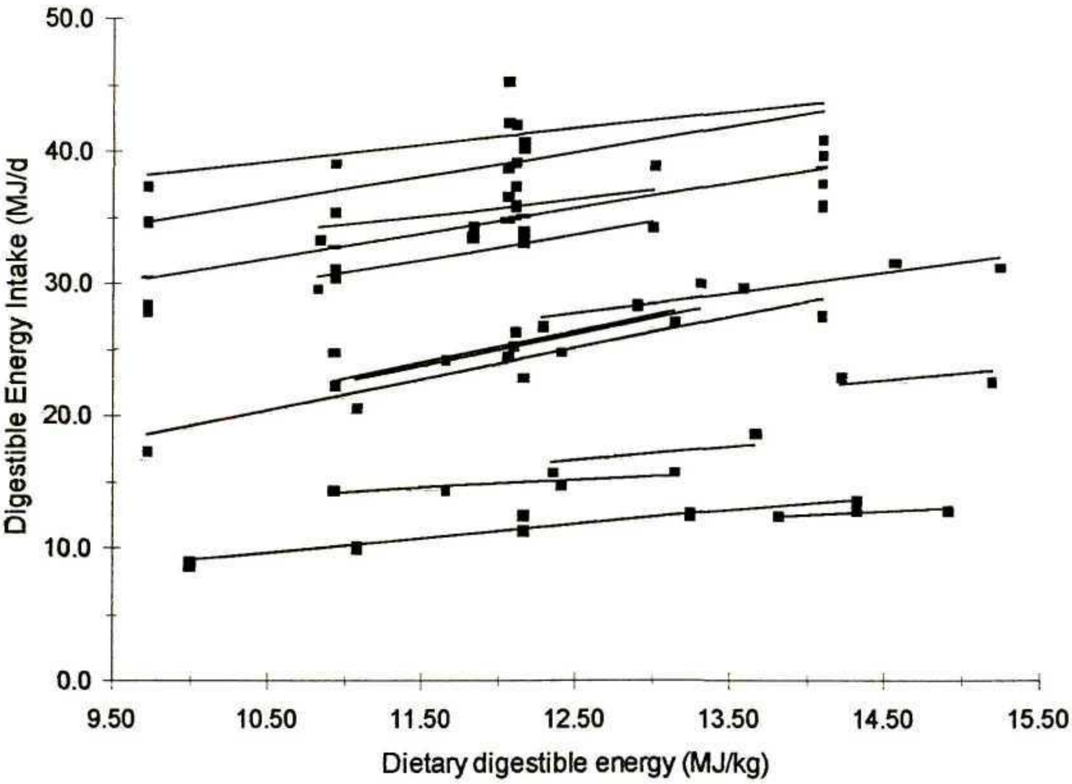

Figure 3.2. Relationship between digestible energy intake and dietary digestible energy. (—) Fitted values from regression model incorporating live weight and genotype effects; (■) published data.

3.4.3 *Response in Live Weight Gain to DE*

The responses in ADG (Figure 3.3) were more variable (R^2 = 81.7%) than those of FI, DEI and FCE. Between experiments the constant terms were significantly different but the rates of ADG change were the same. On average ADG increased 37.5 g/d for every unit increase in DE, which was a significant rate of change ($P < 0.001$). However this response was affected by both genotype and live weight (Table 3.4) with noticeable increases in the rate of change for Lean type pigs in both the 10-30 kg and 30-60kg weight categories but no apparent differences in the rate of response in Fat genotypes across all weight categories. The inclusion of the effects of genotype and live weight increased the amount of variation accounted for to 88.9%.

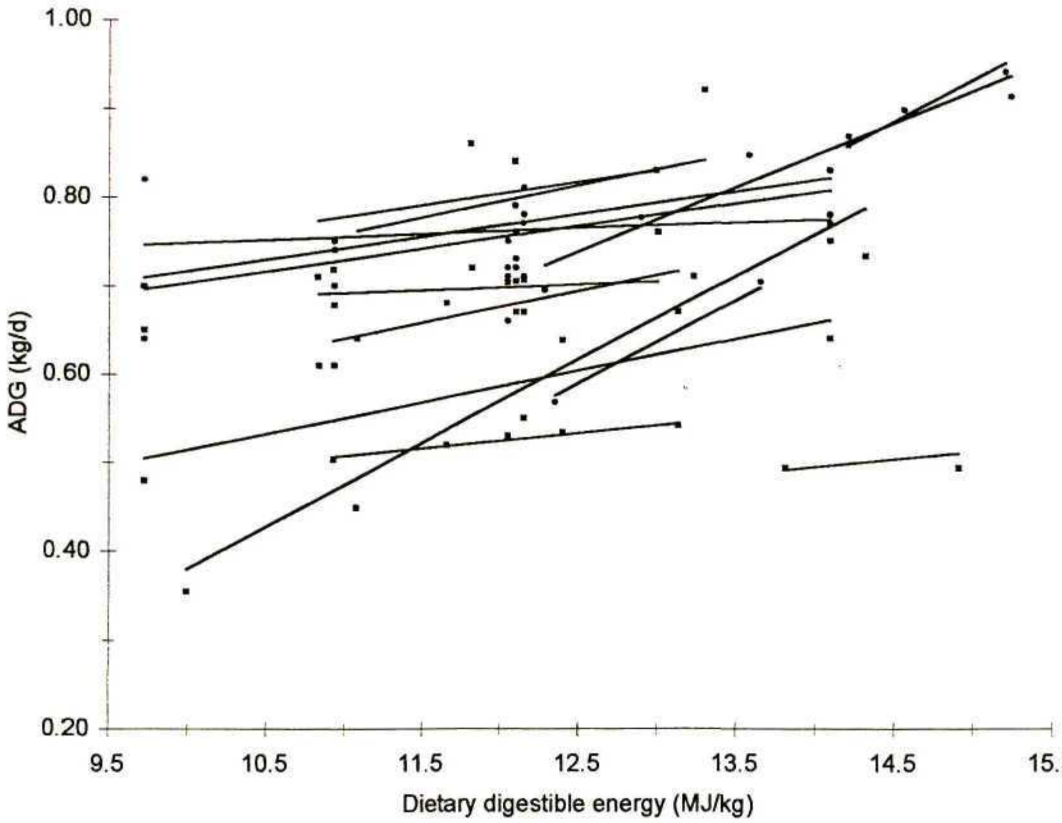

Figure 3.3. Relationship between average daily weight gain (ADG) and dietary digestible energy. (—) Fitted values from regression model incorporating live weight and genotype effects. (■) published data.

3.4.4 Response in Feed Conversion Efficiency to DE

Although the linear model in Equation 1 accounted for most of the variation between experiments (R^2 = 92.6%) without considering the effects of genotype and live weight there was an improvement in response with the inclusion of these two variables (R^2 = 98.7). Most of the variation was accounted for by fitting different constant terms for trials with a common slope. The mean slope of FCE on DE was 29.69 g/kg per MJ /kg DE but the slope was higher for lighter pigs (10-30 kg) and also for Lean pigs in the 30-60 kg live weight range.

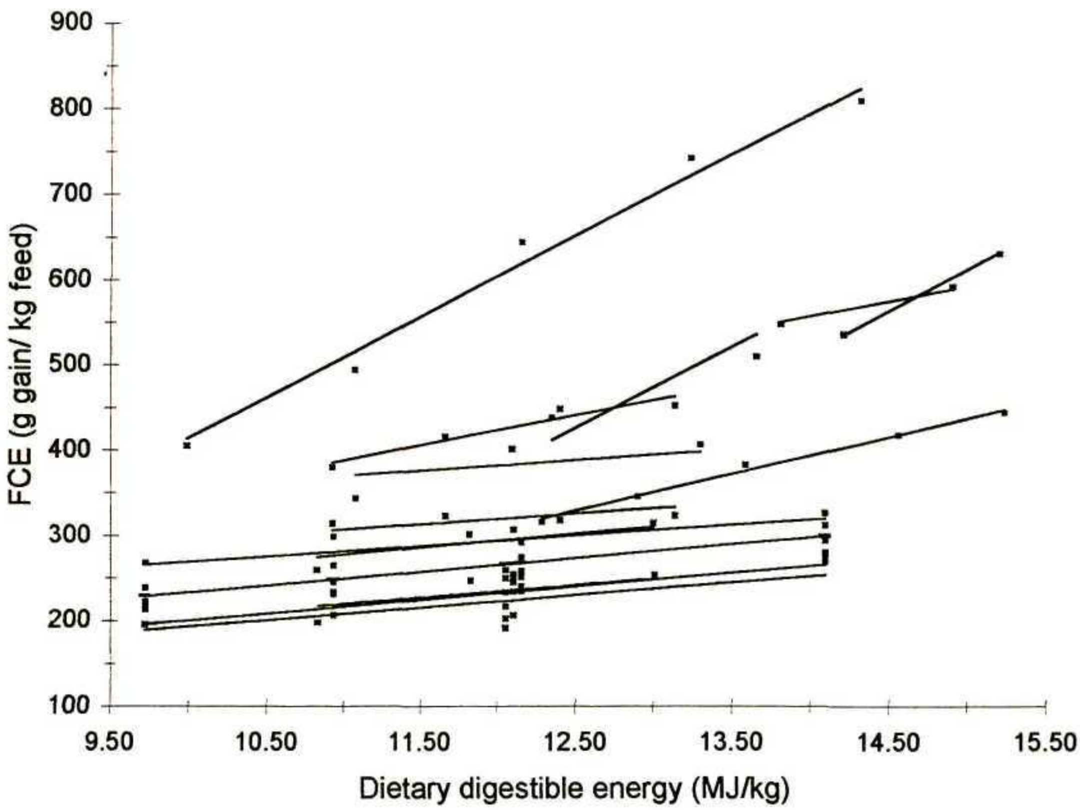

Figure 3.4. Relationship between efficiency of feed conversion (FCE) and dietary digestible energy. (—) Fitted values from regression model incorporating live weight and genotype effects; (■) published data.

3.4.5 Determination of Optimum Nutrient Density

To determine the optimum returns over feed costs and hence the optimum dietary energy concentrations, the levels of production and the rate of response must be defined. The corollary to this is that optimum energy levels are a consequence of both the level of production and the rate of response in production with dietary energy. In the case of pork production the marketing of pigs is at a fixed live weight, irrespective of age, and therefore with a known change in live weight the response to FCE becomes important. In this exercise the level of performance is defined as a live weight change of 20, 30 and 30 kg over the 10-30 kg, 30-60 kg and 60-90 kg periods, respectively and combined with response data for FCE the total feed consumed and feed costs for each weight interval were determined. For a given carcass price/kg it was then possible to calculate the margin over feed costs per pig. From these calculations the energy levels which will maximise the margin over feed costs per batch of pigs were estimated for a number of different production scenarios including different types of pigs, different fixed costs and different lysine:energy ratios.

So as to follow commercial practice, market related feed prices were used to formulate a series of diets differing in nutrient densities. The costs of these feeds are shown in Table 3.2. After considering the various response data and knowing the change in live weight, the response of FCE to DE was used to determine feed costs. This eliminated the need to estimate the number of days pigs would be on a certain feed in order to calculate total feed costs over the growing period from 10 to 90 kg.

The lack of data over the 60 - 90 kg live weight range for the more recent genotype (Lean) required the assumption that the efficiency of feed utilization was approximately 85 percent that of the previous weight range (30 - 60 kg). This assumption was based on the work done by Campbell *et al.* (1985a,b) and others (SCA, 1987) who estimated the range in FCE over the 30-60 kg and 60-90 kg categories to be 0.46 to 0.38 and 0.38 to 0.34, respectively. To accommodate this reduction in efficiency it was assumed that the rate of change in FCE was 0.85 the slope value of the previous weight range.

3.4.6 *Effect of Live Weight*

As there were significant differences in the response of FCE to DE between the various live weight ranges (Table 3.4) it was necessary to incorporate these changes by predicting the feed costs for each weight range separately. Over the live weight ranges 10-30 kg, 30-60 kg and 60-90 kg, it was assumed that for each energy level the lysine :energy ratio would change from 0.75, 0.65 and 0.55 g/MJ respectively. Figure 3.5 shows the differences in margin over feed costs when using the average constant term and single slope value over all experiments to calculate the food intake and hence feed costs versus dividing the growth period of both the Fat and Lean genotypes into the three different weight groups and using their respective FCE responses to DE. The former response to DE does not consider the effects of live weight on FCE and tends to overestimate FCE particularly at higher live weights. Unless specifically stated all discussion refers to responses based on dividing the growing period into the three live weight periods and using the appropriate lysine:energy ratios for all energy levels.

According to Figure 3.5 if a single FCE equation were used to estimate food consumption then it would pay to feed a diet of 11.0 MJ/kg DE over the whole growing period. If one considers the effect of genotype and the associated reduction in FCE with live weight the optimum dietary energy level would be 10.5 MJ/kg for fatter genotypes and 13.5 MJ/kg for modern genotypes. This assumes that one is feeding three different diets over the three different weight ranges. The discrepancy in recommended energy level is probably due to the overestimation of FCE and therefore both food consumption and total feed costs are underestimated. This is particularly noticeable on low energy levels where feed intakes should be much higher. The result is a bias toward the use of low energy diets because they cost less and are not prejudiced by an expected increase in food intake.

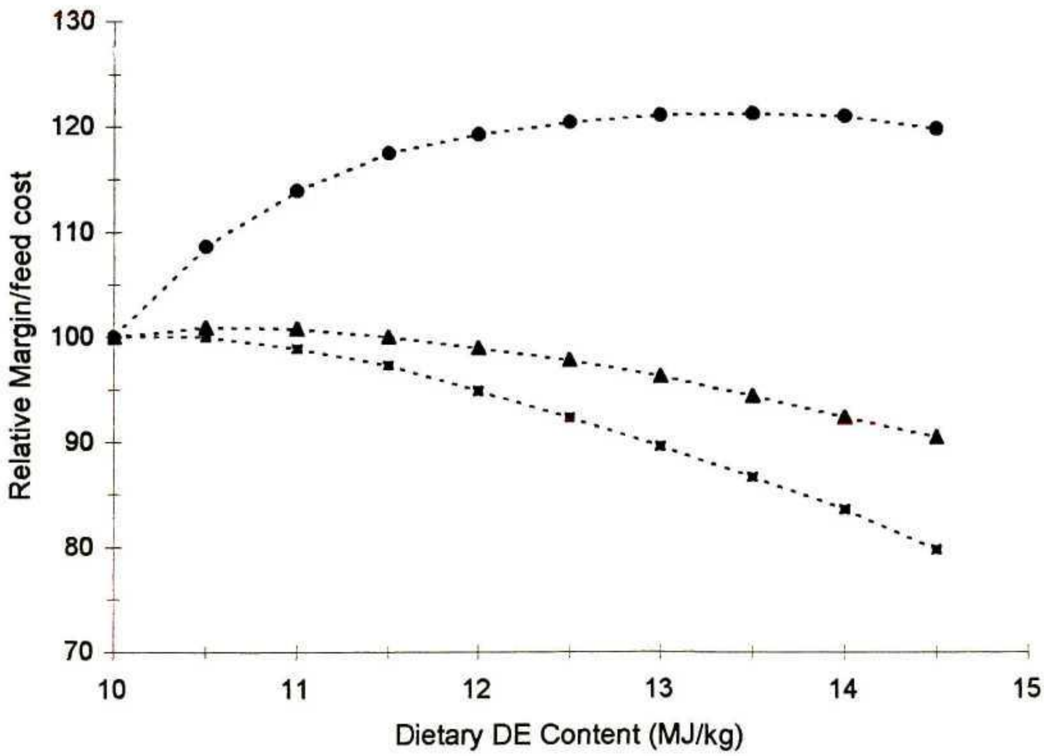

Figure 3.5. *Relative Margins over feed cost (100 = 10 MJ/kg) for balanced diets at different energy levels for growing pigs between 10 and 90 kg live weight. (- - ▲ - -) represents the response to using FCE = 10.58 + 29.687 x DE across all weights to determine food intake. The response to using different equations for 10-30kg and 60-90kg weight ranges is indicated by (- - ● - -) for lean genotypes and (- - ■ - -) for fat genotypes.*

From a production point of view it is important to consider what energy levels would result in minimum feed costs during the growing period. Ideally it would be necessary to provide numerous different weight groups. However, due to the limitations already discussed, this paper will only consider three weight groups. Figure 6 shows the within-weight group response of feed costs to DE concentration. Feed cost rather than margin over feed costs is used because of the difficulty in placing an intrinsic market related value on a 30kg pig.

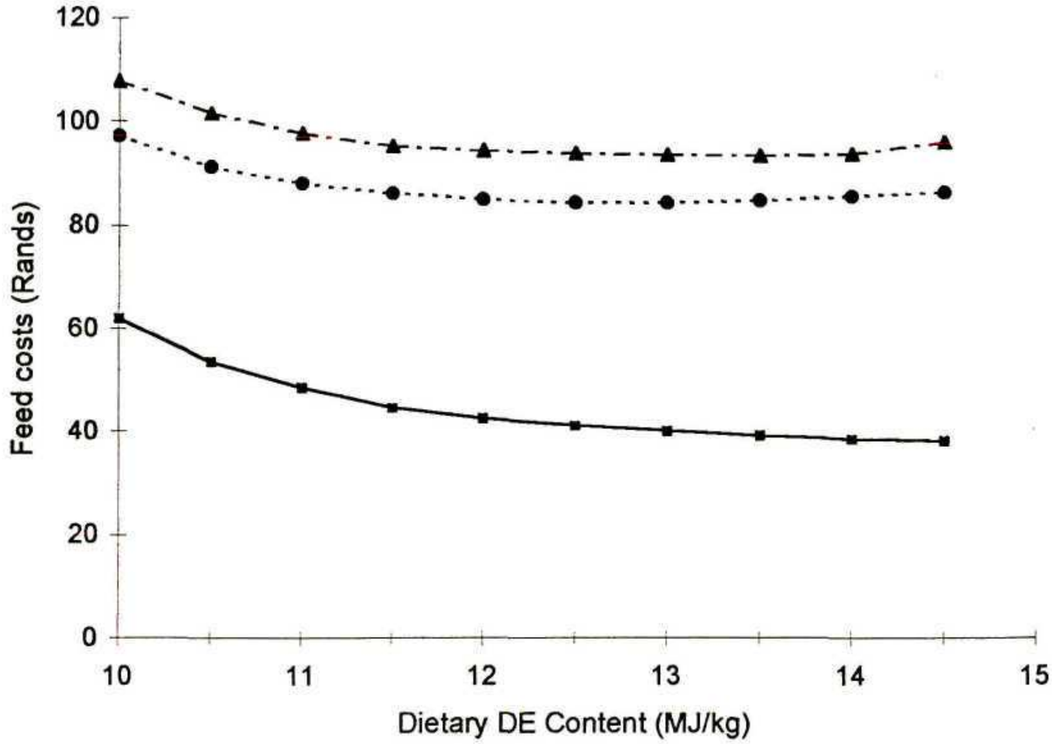

Figure 3.6 *Cost of feed over 3 different live weight periods at different dietary energy levels for growing pigs.*

(–■–) 10-30 kg live weight using 0.75g lysine/MJ DE;

(- - ● - -) 30-60 kg live weight using 0.65g lysine/MJ DE;

(-·- ▲ -·-) 60-90kg live weight using 0.55g lysine/MJ DE.

From Figure 3.6 it is clear that it would pay to feed high energy levels (at least 14.5 MJ/kg, 0.75 g lysine per MJ DE) to modem genotypes during the early growing period (10 to 30 kg) and then decrease the levels to 13.0-13.5 MJ/kg for the 30 to 60 and 60 to 90 kg weight intervals (0.65 g lysine/MJ DE and 0.55 g lysine/ MJ DE). These values are similar to those recommended in the literature (Campbell *et al.*, 1985a). It is important to note that using empirical linear models to estimate optimal responses to energy over various weight periods does not consider the carry-over effect of differences in growth rate and carcass composition on the subsequent growth phase. Taking the different energy levels that resulted in minimum feed costs for each weight range and applying them will result in the optimum feeding strategy in terms of maximizing margin over feed costs. Figure 3.7 compares the response of using the same energy levels for the three different weight ranges with using those energy levels that minimized feed costs in each of the respective weight groups. It is clear that feeding to minimize feeding costs for each growth period will improve profitability. The difficulty in practice is to define which energy level will minimize feed costs over what live weight range.

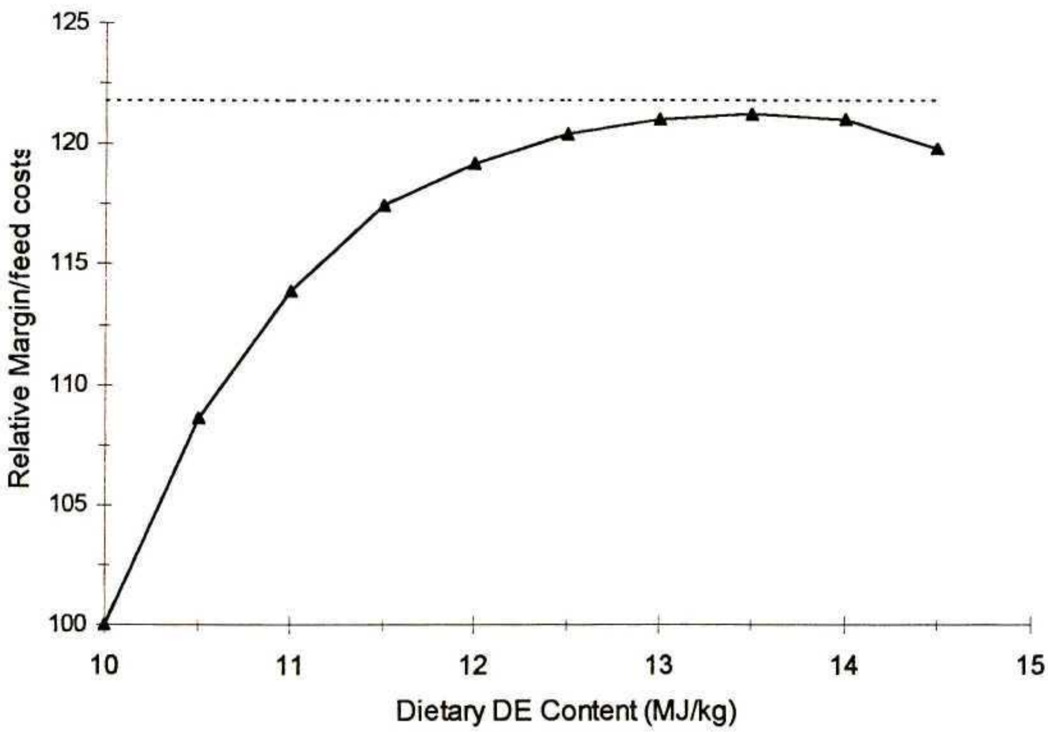

Figure 3.7 *Margin over feed costs at different dietary energy levels for growing pigs. (– ▲ –) represents the response using the same energy level for the 10 – 30 kg, 30 – 60 kg and 60 – 90 kg weight period. (– – –) is the response using the same energy levels that resulted in the lowest feed costs in each of the respective weight groups as shown in Figure 3.6.*

3.4.7 *Effect of Genotype*

A further practical consideration in formulating feeds to optimize productivity is what energy levels should be required for different types of pigs. There are considerable differences in response to energy in the literature partly because of differences in pigs used in the experiments (O'Grady and Bowland, 1972; Kyriazakis and Emmans, 1995). From the FCE results in Table 3.4 it is clear that there will be differences in margin over feed cost responses to DE between different types of pigs. The slower, fatter growing type pig will require lower energy levels to attain maximum efficiency as compared to the faster, leaner growing pig. The extent of the differences will depend on the specific genotype of pigs. Figure 3.5 compares the response to energy between Lean and Fat type pigs with fatter pigs requiring lower energy levels than leaner pig to maximise profits or that the lean type of animal can utilize more energy for the deposition of lean. Although the categorization into Fat and Lean type pigs is an oversimplification of the many different types of pigs it does highlight the principle that different genotypes have different optimum nutrient densities. Formulating one feed for a range of genotypes is a major constraint to optimizing profitability and should be avoided. Figure 3.5 indicates that it does pay to feed pigs according to their growth potential.

3.4.8 *Effect of Lysine:Energy Ratio*

Another important nutritional consideration is what lysine:energy ratio should be used for a given dietary energy level to optimize profits. As protein sources and specifically amino acids are the most expensive components of any ration, the lower the levels the cheaper the ration. However, cheaper rations may not necessarily mean higher profits. Figure 3.8 illustrates the effect of increasing the lysine:energy ratios on profitability.

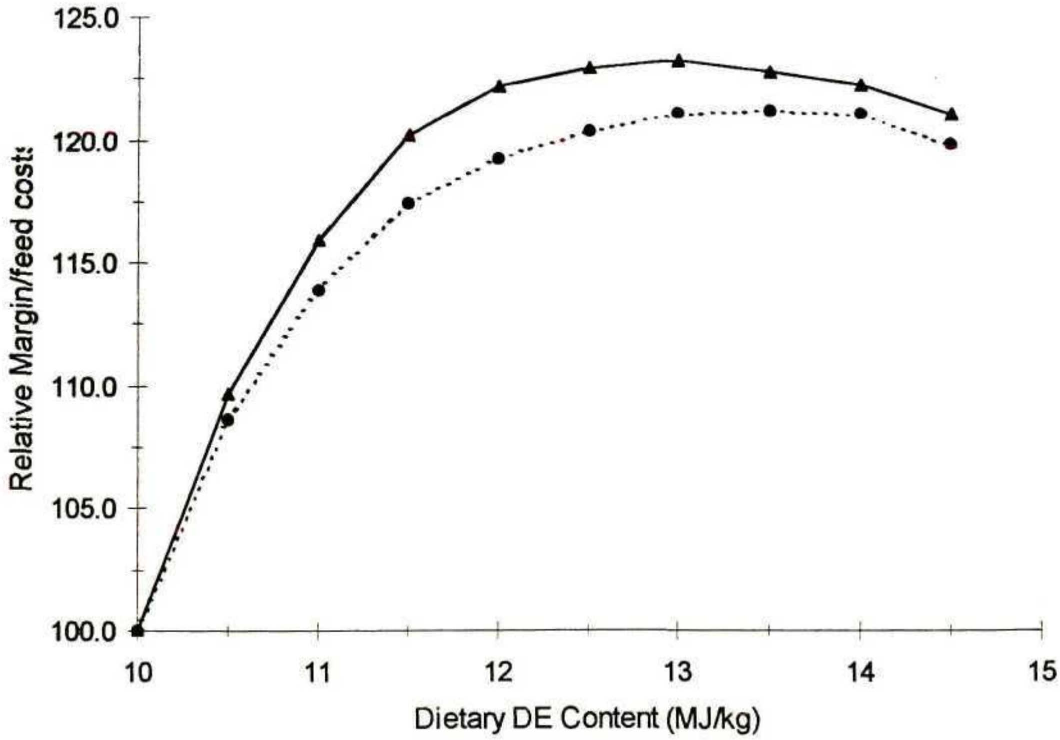

Figure 3.8. *Margin over feed costs at different dietary energy levels for two different sets of lysine:energy ratios over three weight periods. (- - ● - -) 0.75, 0.65 and 0.55 g/MJ and (—▲—) 0.80, 0.75 and 0.70 g/MJ were used over the range 10-30kg, 30-60kg and 60-90kg respectively.*

The indications are that when the lysine:energy ratios are increased, the optimum energy content decreases. A reduction in body fat, an improvement in ADG and FCE are the likely biological responses to an increase in the lysine:energy ratio (Lawrence, 1977; Kyriazakis *et al.*, 1995). These improved biological responses would suggest a possible increase in profitability through reduced time to market and superior carcass quality, and hence it could be argued that optimum dietary energy levels should be higher with an increased lysine:energy ratio. However, where the market price is fixed, irrespective of rate and composition of growth, and the cost of feed is the only determinant of profit margins the effect of an increase in lysine:energy ratio on the response to DE will be to select a feed with a lower energy content so as to reduce the cost of feed as the amino acid concentration increases.

The extent of the reduction in energy will be sensitive to feed ingredient costs and in particular the cost of added fat and synthetic lysine (assuming it is the most limiting amino acid). The cheaper the source of either fat or synthetic lysine the higher their inclusion level in the high energy diets and therefore the cheaper these will be. This will reduce the difference in response to DE between the lower and higher lysine:energy ratios.

3.4.9 Effect of Additional Costs

The last production scenario to consider is the effect of additional feed surcharges such as those incurred when purchasing a commercial feed including diet preparation and transport costs. For the purposes of this discussion a surcharge of R100/ton of feed was incurred. The results in Figure 3.9 showed that the addition of a fixed increment moved the optimum energy level from 13.5 MJ/kg to 14.0 MJ/kg. The effects of a surcharge favours the higher energy levels because the cheaper, low energy diets require more tonnage to get a batch of pigs to a given finishing weight.

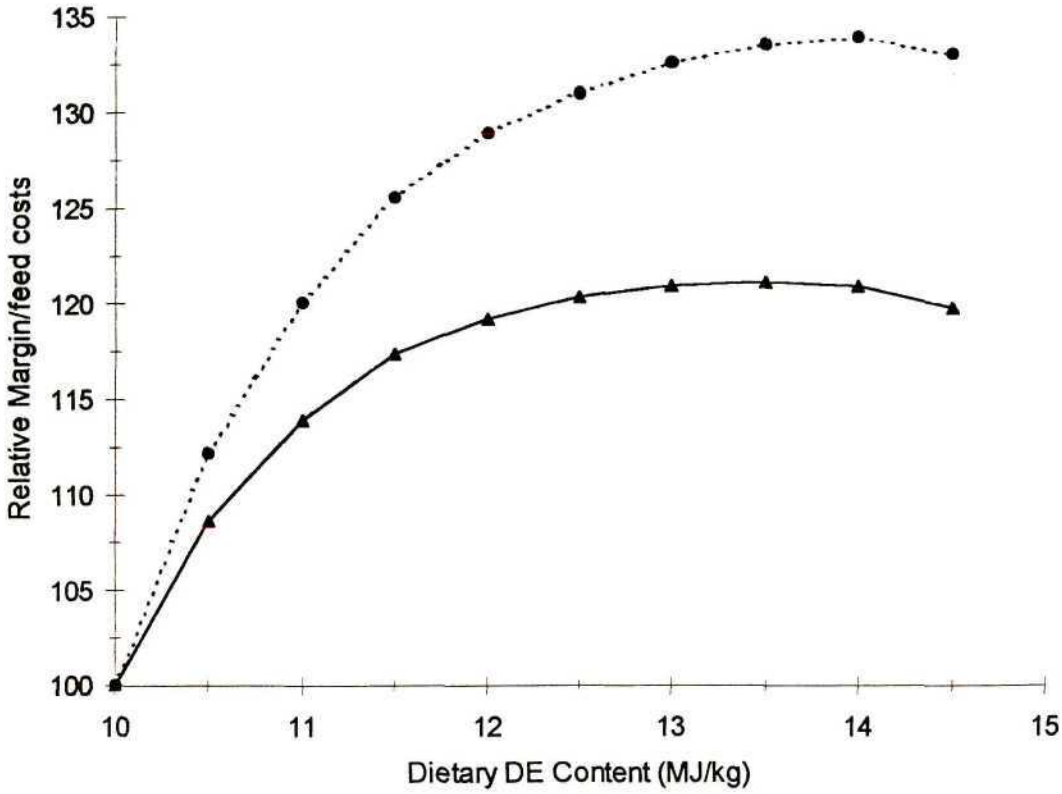

Figure 3.9. *Margin over feed costs at different dietary energy levels with the addition of a R 100/ton fixed cost.*

(–▲–) no fixed cost; (- - ● - -) additional R 100/ton.

Considering the marked effect other incremental costs have on the optimum nutrient density it is recommended that optimum dietary energy concentrations be based on margin over total costs rather than margin over feed costs. Total costs would include fixed costs per pig produced (e.g. cost of producing weaners) and costs per pig per day (e.g. labour) both of which will change the optimum energy level. Costs based on time will favour higher energy levels that promote faster growth in order to reduce the time taken to slaughter.

In conclusion the results of this paper do not necessarily provide accurate estimates of optimum energy levels for general use. However they do show how estimates of responses can be used by producers to formulate feeds that will improve profitability. With a knowledge of the production level (FCE) and the appropriate rate of change (Table 3.4) a producer can determine the optimum energy level. To obtain more accurate estimates of the optimum nutrient density "local" feed and market prices are required. Therefore, with more accurate levels of production it is possible to design feeding strategies including diets and when to feed them, that will optimize profitability.

CHAPTER 4

CHOICES MADE BY GROWING PIGS WHEN GIVEN FEEDS DIFFERING IN NUTRIENT DENSITY

4.1 ABSTRACT

Two experiments were conducted to corroborate or refute the theory that animals will choose a feed that will allow them to maximise the efficiency of feed utilisation. Pigs have been shown to utilise feeds of high nutrient density more efficiently than those of low density, so the choices made by pigs when offered such feeds could be used to test the above optimization theory. In Experiment 1, 48 Large White x Landrace gilts were used, for an eight-week period starting at 22 kg live weight, while in Experiment 2, 48 entire males of the same strain cross were used from 24 to 60 kg live weight. In both experiments use was made of high nutrient density summit feeds (S1, S2 and S3) which were used alone, or diluted in the ratio 80 summit: 20 milled sunflower husk to provide the low density feeds (D1, D2 and D3). In Experiment 1, S1 contained 7.5 g lysine/ kg and 13.20 MJ DE/kg, whereas in Experiment 2 two summit feeds were formulated, the first (S2) being fed from 24 to 40 kg liveweight and the second (S3) from 40 to 60 kg liveweight. Feeds S2 and S3 contained 11.0 and 8.4g lysine/kg respectively and 15.0 and 14.0 MJ/kg DE, respectively. Both experiments made use of a high (HD1 and HD2, respectively) and a low nutrient density (LD1 and LD2, respectively) control treatment in which pigs were given *ad libitum* access to S1 and S2/ S3, and D1and D2/ D3 in Experiments 1 and 2 respectively (n=4). In addition, a medium density treatment (MD1) consisting of a 50:50 mixture of S1 and D1 (n=4) was fed in Experiment 1. Two choice-feeding treatments where used in both experiments, the first in which S1 and S2/ S3 were placed in the left bin (CL1 (n=18) and CL2 (n=20), respectively) and the appropriate dilution diet in the right bin, and the second in which S1 and S2/ S3 were placed in the right bin (CR1 (n=18) and CR2 (n=20)). There were no differences in average daily growth rates between treatments within experiments, but there were significant differences ($P < 0.05$) in food intakes and efficiency of feed utilization (FCE) between treatments. The highest intakes and lowest FCE were obtained on the LD1 and LD2 treatments while the lowest intakes were recorded on the choice-feeding treatments. This suggests that pigs were able to differentiate successfully between two feeds on the basis of their nutrient density and that they selected a diet that maximised their feed conversion efficiency. There were significant differences ($P<0.05$) between choice-feeding treatments on the basis of position of the feed bin, but here was no preference for particular position. This indicates that pigs do not select their diet on the basis of food position.

Keywords: nutrient density, diet selection, pigs, optimization

4.2 INTRODUCTION

A number of choice feeding experiments have been reported in which pigs have demonstrated their ability to choose, from two feeds, a combination that closely matches their changing nutritional requirements through the growing period (Kyriazakis, Emmans and Whittemore, 1990; Bradford and Gous, 1991a,b; Rose and Kyriazakis, 1991). However, no experiments have been reported in which pigs have been offered two feeds having the same nutrient to energy ratio but differing in nutrient density. The choices made by pigs in such a case would not be expected to change systematically through the growing period, as the nutrient to energy ratio, being fixed in both feeds, would not provide the pigs with any combination of the two feeds that would be able to match their changing protein:energy requirement. Yet pigs have been shown to utilise feeds of high nutrient density more efficiently than those of a low density (Ferguson, Nelson and Gous, 1999 – in print) so the choices made by pigs when offered such feeds could be used to corroborate the optimal foraging theory proposed by Krebs and McCleery (1984).

According to the optimal foraging theory (OFT), animals are by nature optimizers and will attempt to perform as efficiently as possible (Krebs and McCleery, 1984). The rationale of OFT is that, when faced with a range of feed sources, an animal makes the decision as to which food or combination of foods to consume, based on a need to perform as efficiently as possible. If an animal is considered as an optimal system then it will seek to obtain resources, such as energy and amino acids, from its environment at a rate needed to support its desired level of performance, without consuming excessive amounts of nutrients (Emmans and Kyriazakis, 1995). Following on from Emmans' (1994) theory of Effective Energy, for an animal to be as efficient as possible it will need to reduce the time spent digesting food in order to increase the amount of available energy, and it may thus prefer a feed high in nutrient density thereby avoiding having to process ingredients of low digestibility. The nutrient density of the food consumed will affect the amount of time and energy the animal will have to spend both eating and digesting the food. In general, the higher the density of the feed the lower he fibrous or indigestible component and hence, the greater the rate of digestion. Therefore, according to OFT it is predicted that animals would select a diet of high nutrient density, in order to minimise the energy expended in eating it, and maximise the efficiency of energy utilisation. The main objective of this research was therefore to test whether the theory of optimality (OFT) holds true for growing pigs, the hypothesis being that pigs would choose a high density food in preference to one of low nutrient density, in order to maximise the efficiency of utilisation of feed.

A second objective of this research was to determine the basis on which the pigs were making a choice: either they were exhibiting the ability to choose according to their requirements for maximum efficiency, or simply making a choice according to the position of the feed trough. To this end, pigs were housed individually in pens, rather than in groups. A major practical advantage of the choice-feeding system, when applied commercially, is that animals with different nutrient requirements may be kept together in a pen, yet each is capable of meeting its requirements by choosing the appropriate combination of the two feeds on offer. Many choice-feeding experiments that have been reported have made use of groups of pigs kept together in a pen (Bradford and Gous, 1991a and b, Bradford and Gous, 1992; Gill *et al.*, 1995). However, when measuring the preferences of pigs in research conditions there is an advantage in having the pigs individually penned rather than in groups. When housed in groups the interpretation of choice-feeding experiments is made more difficult, as the average group response may not represent the choice of an individual. In more recent studies, data have been collected on individually-housed pigs, and this method has proved to be considerably more valuable in understanding the reasons for the choices made (Kyriazakis *et al.*, 1991; Kyriazakis, Emmans and Taylor, 1993). However, the number of replications used in the experiments reported in these two papers was small, resulting in relatively large within-treatment differences, casting some doubt on the validity of the results obtained. In the research reported here, therefore, within-treatment variation was reduced considerably by using a large number of replicates per choice-feeding treatment. This has the effect of reducing the influence of any one individual that has made the "wrong" choice, on the mean treatment response.

4.3 MATERIALS AND METHODS

4.3.1 Animals and Housing

Two experiments were conducted, a year apart, in a housing facility which comprised 48 individual pens within an open-sided house, with a roll-up curtain on the side facing the prevailing winds. In Experiment 1 forty-eight Large White X Landrace gilts, with a starting live weight of 22.9 (±4.43) kg, were used, while in Experiment 2 the same number of Large White X Landrace entire males, initially weighing 24.3 (± 0.43) kg, were used. The animals were randomly allocated to the 48 individual pens (1.0 x 2.1 m) each pen having solid concrete floors. Wood shavings were placed in each pen and these were changed twice a week. The gates and sides of the pens were constructed of tubular metal bars and wire mesh to allow pigs sight and smell of other pigs, as well as providing them with a limited amount of physical contact. Individual pens were equipped with a nipple drinker and two metal feed bins each with an eating area of 0.3 x 0.4m. The position of the feeders within the pens was not changed throughout the experiment and dietary treatments were randomly allocated to each side. Each pig was identified by means of an ear tag.

4.3.2 Feeds

In both experiments a summit diet was used as the feed of high nutrient density, the low density feed being produced by diluting the summit feed with finely milled sunflower husks in the ratio 80 summit : 20 sunflower husk. This ensured that the ratio of nutrients:energy remained the same in both feeds offered in each experiment. In Experiment 1 the high nutrient density diet (S1) was formulated to meet the requirements of the animal from 20 to 70 kg live weight. Additional vitamins and trace minerals were added to the summit and dilution feeds, to ensure that these nutrients were non-limiting. In addition to the two basal feeds an intermediate feed was mixed consisting of equal parts of S1 and D1. For Experiment 2 two summit feeds were formulated, one (S2) for the period 20 to 40 kg live weight and the other (S3) for the weight range 40 to 60 kg. These latter feeds were diluted with milled sunflower husk to produce dilution feeds D1 and D2 respectively. The composition and analysis of all feeds are given in Table 4.1. The nutrient:energy ratio of S2 was higher than S1 because the feed was to be fed to pigs over a shorter live weight range and therefore a higher concentration of nutrients was required.

Table 4.1. Composition and chemical analyses of the experimental feeds (g/kg fresh weight)

	Experiment 1		Experiment 2			
Ingredients	S1	D1	S2	D2	S3	D3
Yellow maize	787.6	630.1	431.0	345.0	482.0	386.0
Sunflower meal	154.0	123.0	181.0	145.0	76.5	61.0
Soybean meal	20.0	16.0	38.0	30.0		
Wheat bran			46.0	36.0	150.0	120.0
Milled sunflower husks		200.0		200.0		200.0
Brown sugar			150.0	120.0	100.0	80.0
Molasses					50.0	40.0
Fish Meal Sunflower Oil			120.0	96.0	89.0	71.0
Salt			5.0	4.0	16.0	12.7
L-Lysine HCl	2.8	2.3	2.0	2.0	4.5	3.6
Monocalcium phosphate	3.7	3.0				
Limestone	9.4	7.6	14.0	11.0	18.0	14.7
Vitamin/Mineral premix	2.5	2.0	2.0	2.0	2.0	1.6
<u>Chemical composition:</u>						
Dry matter	879.5‡	940.2‡	903.5	899.5	898.0	908.0
Crude Protein	139.2‡	111.4‡	200.3	196.0	158.9	143.4
Gross Energy (MJ/kg)			17.84	18.27	16.91	17.39
Digestible Energy (MJ/kg)	13.2‡	10.56‡	14.98	13.02	14.00	12.35
Neutral Detergent Fibre			121.9	241.9	135.9	241.9
Lysine	7.5‡	6.0‡	11.0	9.70	8.40	7.60

† Calculated from DE = 3.77 – (0.019xNDF) + (0.758xGE)

‡ Calculated from tables

4.3.3 *Design*

Experiment 1

This experiment consisted of five dietary treatments: three control treatments and two choice-feeding treatments. Pigs on the three control treatments (n=4) were given free and continuous access to S1 (treatment HD1), D1 (treatment LD1), or a 50:50 blend of S1 and D1 (treatment MD1), respectively. The remaining 36 pigs were placed on the choice-feeding treatment, where they were offered both S1 and D1 simultaneously. Eighteen of these pigs were given S1 in the left bin and D1 in the right (CL1), while with the other 18, the opposite combination was used (CR1). The large number of replicates allocated to the choice feeding treatment was designed to reduce the within-treatment variation often encountered with choice feeding experiments. Pigs were allocated randomly to treatments. The duration of the trial was eight weeks.

Experiment 2

This was similar in design to Experiment 1 but with the exclusion of the blended treatment. Two control treatments and two choice-feeding treatments were used. Four pigs on each of the two control treatments were offered *ad libitum* access to either S2 (treatment HD2) or D2 (treatment LD2) from 24 kg to 40 kg live weight, and then diets S3 or D3 from 40 kg to 60 kg live weight. The remaining 40 pigs were offered a choice of S2 and D2 from 24 to 40 kg, and S3 and D3 until 60 kg live weight. Twenty of these pigs were given S2 (later S3) in the left bin and D2 (later D3) in the right (treatment CL2), with the opposite combination being used for the remaining twenty pigs on the second choice-feeding treatment (CR2). Both pigs and treatments were allocated randomly to treatments and pens, respectively. The trial ended when all pigs reached 60 kg live weight.

In order to accustom the choice-fed pigs to the diets available, a seven-day adaptation period was provided prior to the start of each experiment. Pigs were allowed access to only one of the two foods on alternate days during this training period.

4.3.4 Management Procedures

The management procedures were the same for both trials. Pigs were weighed individually once a week and then twice a week as the heaviest animals approached the final live weight for the experiment. Food remaining in the troughs was weighed weekly, from which data the total food intake for each pen for the preceding week was determined.

4.3.5 Analysis of the Results

The results were subjected to an analysis of variance as a completely random design using Minitab (1993). Specific comparisons between treatments were made by means of a Student's *t* – Test. Linear regression analysis were used to determine weekly differences in the proportion of high density diet consumed between the left and right feed bins. In Experiment 1 there were large differences in initial live weight between animals and therefore covariance analysis was used with initial body weight as the covariate.

4.4 RESULTS AND DISCUSSION

4.4.1 Biological Responses to Dietary Treatments

The effects of the dietary treatments on daily food intake, growth rate, food conversion efficiency (FCE), digestible energy (DE) intake and lysine intake are shown in Tables 4.2 and 4.3 for Experiments 1 and 2, respectively.

Table 4.2. *Experiment 1: Daily food intake (FI), average daily weight gain (ADG), food conversion efficiency (FCE), DE intake (DEI) and lysine intake (LysI) of pigs for an eight week period starting at 22 kg live weight after adjusting for covariance with initial body weight as the covariate.*

Treatment	FI (kg/day)	ADG (kg/day)	FCE (g gain/kg food)	DEI (MJ/d)	LysI (g/d)
HD1	2.326	0.710	324	28.849	16.4
LD1	3.164	0.666	207	33.886	19.3
MD1	2.669	0.658	261	30.424	17.4
CL1	2.230	0.685	305	29.167	16.6
CR1	2.459	0.707	292	30.468	17.3
s.e.d. : †					
Single feeding	0.280	0.059	29.1	3.075	1.75
Choice feeding	0.132	0.280	13.7	1.450	0.82
Single vs Choice	0.219	0.046	22.7	2.404	1.37
Significance	**	NS	***	NS	NS

† Unequal number of replications: Between single feeding (n=4); Between Choice feeding (n=18); and Single versus Choice (n=4 and 18 respectively)

Table 4.3. Experiment 2: Daily food intake (FI), average daily weight gain (ADG), food conversion efficiency (FCE), DE intake (DEI) and lysine intake (LysI) of pigs from 25 kg to 60 kg live weight.

Treatment	FI (kg/day)	ADG (kg/day)	FCE (g gain/kg food)	DEI (MJ/d)	LysI (g/d)
HD2	2.008	0.740	369	28.40	18.80
LD2	2.277	0.735	322	28.41	19.14
CL2	1.979	0.706	357	27.78	18.41
CR2	1.955	0.699	358	27.70	18.36
s.e.d. : †					
Single feeding	0.133	0.053	15.6	1.855	1.213
Choice feeding	0.059	0.024	7.0	0.830	0.542
Single vs Choice	0.103	0.041	12.1	1.437	0.939
Significance	*	NS	*	NS	NS

† Unequal number of replications: Between single feeding (n=4); Between Choice feeding (n=20); and Single versus Choice (n=4 and 20 respectively)

A measurable consequence of any diet selection process will be an improvement in feed conversion efficiency as the animal attempts to minimise excess nutrient or non-nutrient (crude fibre) intakes. The results in Tables 4.2 and 4.3 show that in both experiments, pigs on the control treatments HD1 and HD2 utilised their feed more efficiently than those on LD1 and LD2, respectively. Although they did not grow any faster, they consumed significantly less food ($P < 0.05$). The response of pigs on treatment MD1 in Experiment 1 fell between those of HD1 and LD1. There were no significant differences between the responses of pigs on the choice-feeding treatments compared with those on HD1 and HD2 in either Experiment 1 or 2. However, pigs on HD1, on HD2, and on the choice-feeding treatments consumed significantly less feed (Experiment 1: $P < 0.001$; Experiment 2: $P < 0.01$) and were more efficient converters of food (Experiment 1: $P < 0.001$; Experiment 2: $P < 0.01$)

than their counterparts fed only LD1 and LD2, respectively.

The increased DE and lysine intakes associated with lower nutrient density diets (LD1, MD1 and LD2) was symptomatic of an animal attempting to meet its nutrient requirements. These results strongly suggest that, given the choice, pigs would rather consume a feed that will allow them to grow as efficiently as possible than eat to satisfy a certain minimum gut capacity, thereby corroborating the OFT. Emmans (1994) has provided evidence that there is an energy cost associated with defaecation, or the elimination from the body of faecal organic matter. To minimise such energy expenditure the animal could be seen to prefer a feed that is low in indigestible organic matter, and would therefore prefer a high density rather than a low density feed. The results of these experiments provide evidence to support such a theory.

Ferguson *et al* (1999) analysed the results of a number of publications in which pigs were offered single feeds differing in nutrient density, and they concluded that pigs utilised feeds of high nutrient density more efficiently than feeds of lower nutrient density. However, the economic optimum nutrient density is not necessarily, or usually, the highest feasible nutrient density, even though pigs consume less feed as nutrient density is increased. The prices of the ingredients incorporated into such feeds are higher than those required in lower density feeds, making such feeds more expensive to produce. The cost of feeding, and the income derived from feeds differing in nutrient density will therefore determine the economic optimum nutrient density of feeds for pigs, and this optimum will differ with the circumstances under which the pigs are kept. An interesting question is what nutrient density the pig would choose if given the choice between a high- and a low-density feed. The animal might choose the higher nutrient density diet as a means of maximising feed efficiency (Ferguson *et al*, 1999), but it is conceivable that pigs may prefer to spend more time feeding and have a greater gut fill, in which case they would choose the lower nutrient density diet.

Kyriazakis and Emmans (1991) and Emmans (1991) applied the OFT to suggest that animals will eat an amount of a given feed, or a choice of feeds, that will satisfy their nutrient requirements, and once these nutrient requirements have been met there is no need to consume more food. They suggest that animals will not only try to meet their requirements, but they will attempt to minimise excess nutrient intake in order to reduce the energy cost, in terms of heat produced, incurred in processing the feed consumed. For a more detailed explanation of the theory of food intake regulation, refer to the paper by Emmans (1994). Therefore, the amount of feed the animal will attempt to eat will depend on the specific requirements of the animal and the nutrient content and availability of the feed consumed. The lower the concentration of nutrients the more feed the animal will have to eat in order to satisfy its requirement. In addition, the energy cost of processing the feed will be higher and the efficiency of feed utilization will be reduced. The converse is true for higher nutrient density diets (Ball and Aherne, 1987; Kyriazakis and Emmans, 1995). The results in this paper show that where pigs were fed a single high nutrient density diet they grew at a similar rate to animals fed a lower nutrient density diet, but they consumed less food and were more efficient, confirming the conclusion reported by Ferguson *et al.* (1999).

Within experiments, neither energy nor lysine intakes were significantly different between treatments, however, there was a tendency for pigs on LD1 and LD2 to overconsume energy and lysine relative to that consumed on HD1, HD2 and the choice-feeding treatments. It has been reported that pigs overconsume lysine when given a choice between two diets differing only in protein content (Nam and Aherne, 1995). Although the diets offered in the present experiment differed in energy as well as protein, the lysine intakes in both experiments were either the same or slightly lower in the choice-feeding treatments than in single-fed HD1 and HD2 treatments. This would substantiate the theory that pigs eat just sufficient of a given feed to satisfy their nutrient requirements.

4.4.2 Composition of Diet Selection

The effects of nutrient density and position of feeds on the composition of the diet selected by pigs given access to a pair of foods over the experimental live weight range, per week, are shown in Tables 4.4 and 4.5, respectively.

Table 4.4. The amount of high density feed selected from the left and right feed-bins, as a proportion of the total food intake (TFI), by pigs given a choice between two feeds, for an eight week period starting at 22 kg (Experiment 1) and 24 to 60 kg (Experiment 2) live weight.

	Proportion of high density feed selected (g/g TFI)					
Experiment (weight range)	Left bin	Right bin	s.e.d.	P	Average	s.e.m.
Experiment 1: (22-75kg)	0.862	0.666	0.031	***	0.764	0.029
Experiment 2: (24-60kg)	0.899	0.971	0.040	NS	0.935	0.020

Table 4.5. Regression analyses of the amount of high density feed consumed, as a proportion of total feed intake (TFI), over time from the left and right bins in Experiment 1 (8 week period) and 2 (6 week period).

Position of bin	Constant term	s.e.	Regression coefficient	s.e	R^2
Experiment 1:					40.8
Left bin	0.799	0.031	0.014	0.006	78.4
Right bin	0.788	0.044	-0.025	0.009	78.4
Significance:	NS		***		
Experiment 2:					
Left bin	1.005	0.028	-0.024	0.006	79.2
Right bin	0.939	0.013	0.008	0.003	69.3
Significance:	NS		***		

Over the eight week period from 22 kg live weight in Experiment 1 there were statistically significant differences in the total amount of S1 consumed from the left (CL1) and from the right (CR1), with a preference being apparent for S1 when offered in the left bin (Table 4.4). However, in the equivalent period (to 60 kg live weight) in Experiment 2 the opposite occurred, with the preference being for the high density feed in the right-hand bin (CR2), but in this case the differences were not significant (Table 4.4). Similarly, there were differences over time in the proportion of S1 and S2 selected between the left and right bins (Table 4.5), these differences being apparent in both experiments, but no trend was evident in either case. The results of the regression analyses in Table 4.5 indicate that the amount of S1, in Experiment 1, and S2, in Experiment 2, consumed from each bin, as a proportion of the total feed intake (TFI), changed with time. However, the rates of change between experiments and between bin positions proved to be significantly different ($P < 0.001$). Within each experiment there was no difference in the initial amount of S1 consumed (constant term in Table 4.5) from each bin, but in

Experiment 2 the initial amount of S1 consumed was significantly higher ($P<0.05$) than in Experiment 1.

Since nutrient requirements of growing animals, when expressed as a concentration in the feed, are expected to be high initially and then to decline steadily as the animal grows toward maturity, if the animal is given a choice between two feeds differing in nutrient:energy ratio, the composition of the diet selected would be expected to change with time. In previous choice-feeding experiments (Kyriazakis *et al.*, 1990; Bradford and Gous, 1991b; 1992), pigs have shown nutritional wisdom by selecting, from a choice of diets differing in protein content, a diet that reflects their changing protein requirements with age. The pigs consumed proportionally more of the higher protein feed at a younger age when food intakes were low and relative protein requirements high, but this proportion declined with age. In the experiments reported here, the nutrient:energy ratio was the same in both feeds on offer, and therefore the animal has no reason to change feeds over time. In Figure 4.1, the weekly changes in diet selection in the present experiments are illustrated. Although the trend is for a gradual decrease in the proportion of the higher density feed selected, the slopes are not significantly different from zero in either experiment.

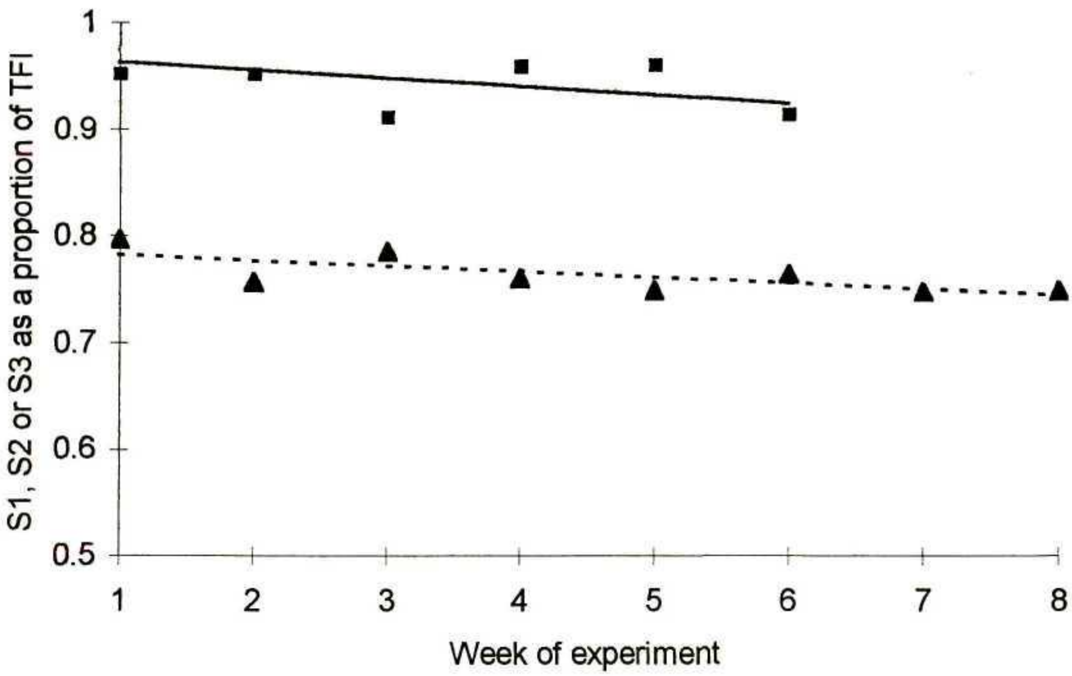

Figure 4.1. *The amount of high density feed (S1 in Experiment 1; S2 and S3 in Experiment 2) selected as a proportion of the total amount of feed consumed (TFI) over time. (▲) S1; (---) fitted response of S1 ; (■) S2 and S3; (—) fitted response of S2 and S3.*

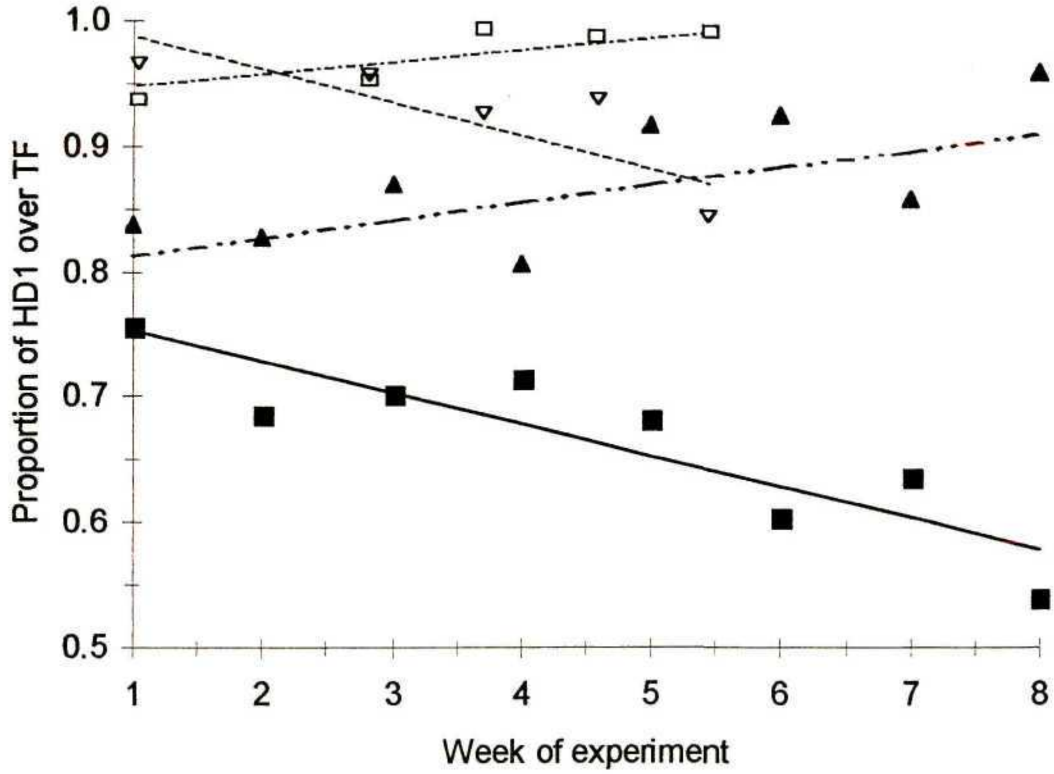

Figure 4.2. *The amount of high density feed (S1) selected from the left and right bins, as a proportion of the total amount of feed consumed (TFI) over time in the two experiments.*

(▲) S1 in left bin, Experiment 1; (–· ·–) fitted response of S1 in left bin, Experiment 1;

(■) S1 in right bin, Experiment 1; (——) fitted response of S1 in right bin, Experiment 1.

(▽) S2 in left bin, Experiment 2; (– – –) fitted response of S1 in left bin, Experiment 2;

(□) S2 in right bin, Experiment 2; (-·-·-) fitted response of S1 in right bin, Experiment 2.

From Table 4.5 and Figure 4.2 it is clear that there were significant differences ($P<0.001$) in the composition of diet selected as a result of the location of the high nutrient density feed, but there was no trend. In Experiment 1, placing S1 in the left bin resulted in a greater proportion of S1 relative to TFI being consumed over time than when this feed was placed in the right bin. However, placing S1 in the right bin resulted in pigs selecting proportionally less of S1 as they grew older and more of D1, which was in the left bin. Given the ample feeding space and easy access to both bins there is no logical nor behavioural reason why pigs should have exhibited a preference for bin position. As if to prove the point, the opposite result occurred in the second experiment, with the amount of S2 and S3 consumed, as a proportion of TFI, decreasing with time in the left bin and increasing in the right bin. This contradiction in response between the two experiments would suggest that pigs do not select feed on the basis of feed-bin position, but rather according to their nutritional needs.

Whereas high nutrient density feeds were preferred by pigs in the experiments reported here, such high density feeds are not usually cost-effective because of the high cost of ingredients that must be incorporated into them. Generally, as ingredient costs increase relative to the returns from the sale of product, the optimum economic nutrient density will decrease even though pigs on high nutrient density diets will consume less food and utilize the food more efficiently (Ferguson *et al.*, 1999). From a commercial point of view, therefore the use of a choice-feeding system, in which feeds of different nutrient density are offered, is not to be recommended. The experiments reported here were not designed to determine a commercially viable feeding system, but instead were designed to corroborate the theory that animals will choose a feed that maximises the efficiency of utilisation of that feed. The evidence presented here supports the OFT and the theory proposed by Emmans (1994) that energy is expended in voiding faecal organic matter. If given a choice, pigs appear to prefer a feed which minimizes the expenditure of energy for non-productive purposes.

GENERAL DISCUSSION

The analysis of growth response curves of pigs to changing dietary nutrient density extracted from the literature provided convincing evidence that the response of pigs to changing dietary nutrient density is indeed analogous to those responses determined in broilers. The responses in energy intake, weight gain and feed conversion efficiency (FCE) were all found to be of a linear nature, with the slope (indicated by the regression co-efficient) of the response line being the important measurement in the analysis of these responses. As with broilers, pigs increase their dietary energy intake as the dietary energy concentration of the feed is increased, leading to an improvement in FCE at higher nutrient densities.

This analysis has distinguished the fact that pigs utilise feeds of high nutrient density more efficiently than feeds of lower nutrient density, but the highest nutrient densities need not be the most economic to feed. Since the optimum nutrient density is that at which the income minus feed cost is highest, the rates of response in production and in consumption, to a range of dietary energy concentrations, need to be converted into monetary amounts in order to determine the optimum nutrient density.

However, the level of production is affected by both genotype and liveweight, resulting in different optimum nutrient densities for different scenarios. For example, a slower growing, fatter genotype has been shown to utilize a diet of low nutrient density better than a faster growing, leaner type pig. Furthermore, the responses have been shown to vary for different growth periods, which means that the most profitable nutrient density may differ during these growth periods. This latter difference is brought about partially because of differences in the amino acid:energy ratio required by pigs at different stages of growth, but also because the responses vary according to age (Fisher and Wilson, 1974).

Considering that these factors all affect the optimum nutrient density, it is interesting to add another dimension by elaborating on the choices made by pigs when faced with two feeds differing in nutrient density. The accurate execution of these experiments necessitated the application of a formal problem solving approach to the issue of feed spillage within the experimental pens. An accurate measurement of food intake was essential in these experiments. The finally-chosen design involved reducing the amount of feed available in the bottom of the trough to discourage pigs from scraping out feed. The altered feeders were then used throughout the growing period, and for the duration of both experiments, to give sufficiently accurate and acceptable measurements for these trials.

One would expect the results of the two choice feeding experiments to reveal that pigs choose a diet of high nutrient density, since the investigation into past literature revealed that they make most efficient use of this type of feed. Combined with the concept of the optimal foraging theory, which suggests that animals will choose a feed that minimises the cost of procurement of the feed, and Emmans' (1994) effective energy concepts, this would appear to be the most logical choice. This conclusion was confirmed by the results of the two choice feeding experiments which showed that pigs, given a choice of high and low nutrient density diets, selected a diet that was utilised as efficiently as if they were fed a high nutrient density diet alone. They also consumed less feed on this treatment compared with the other two treatments. These results strengthen the theory that pigs will base their choice of feeds on their desire to grow as efficiently as possible rather than to fulfill a minimum gut capacity. Another observation supporting this theory, which was apparent from the results obtained, is that pigs do not appear to make a choice based on the position of the feed bin, but again, according to their nutritional needs. The use of choice feeding as a tool in this research has been noteworthy, the results of which yielded a better understanding of the intrinsic nutritional needs of pigs, rather than as a motive to incorporate the concept into commercial production.

The basis for the optimum nutrient density of feeds chosen by the pigs themselves should be considered as biological rather than economic. The higher nutrient density feeds preferred by the pigs in the choice feeding experiments would not be cost effective, as the ingredients making up such a feed are expensive. The optimum economic nutrient density would be lower than the optimum biological nutrient density, as ingredient costs increase more rapidly relative to the profit on the product as the nutrient density is increased.

In conclusion, this thesis has provided pig nutritionists with the information necessary to determine the optimum nutrient density of feeds for pigs. It is thus possible for the farmer to formulate feeds and design feeding systems over the growth period that have the potential to maximise the profitability of the pig enterprise. Conclusive evidence has also been acquired that refutes the hypothesis that pigs cannot distinguish between two feeds on the basis of the composition of the feeds offered.

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