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STUDIES IN THE AGRICULTURAL AND FOOD SCIENCES

Recent Advances in Animal Nutrition—1983

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PREFACE

The proceedings of the Seventeenth Nutrition Conference for Feed Manufacturers contain chapters on a number of aspects of the nutrition of farm animals which are of topical interest.

The evaluation of nutritional data is of paramount importance to feed compounders who have the responsibility of formulating rations to meet the requirements of the different classes of livestock. It was therefore timely that this general topic be aired. The first chapter within this group considers the number of replicates and other features of the design of field trials to evaluate nutritional products and this is followed by a chapter on the interpretation of response data. The final chapter in this group discusses the various sources of error in estimating the nutritive value of feedstuffs and their effect on livestock production. This will be particularly relevant if declaration of the energy content of compound animal feeds is made compulsory.

The second group of chapters relates to pig nutrition, and include consideration of cereal replacers as alternative sources of energy in pig feeds, the prediction of the energy content of pig feeds from chemical measurements, the use of fat in sow diets and vitamin responsive conditions in breeding pigs.

Two chapters relate to calf rearing, the first involving consideration of the various systems available for rearing calves, and the second considers the composition and use of various types of milk replacers for calves. Other chapters relating to ruminant nutrition consist of a consideration of the nutrient requirements of the breeding ewe, the mode of action and importance of rumen active growth promoters, nutritional aspects of high yielding dairy cows, and feeding dairy cows for high margins. The final chapter concentrates on the controversial issue of copper in animal feeds, and provides a balanced view of why it would be extremely difficult to provide general legislation throughout the whole of the EEC on copper inclusion rates in compound feeds.

All chapters are written in a clear and informative manner and are likely to be of interest to research workers, advisory staff and students alike.

The organizers and the University of Nottingham are grateful to BP Nutrition (UK) Ltd, for the support they have given in the organization of this conference.

W. Haresign

1

THE NUMBER OF REPLICATES AND OTHER CONSIDERATIONS IN THE DESIGN OF FIELD TRIALS

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Introduction

The principles that should apply to experiments in the animal feedingstuffs industry are common to most biological work but do not always seem to be observed. The basic difference between experiments using biological material from ones in a physics laboratory is due to variability. Biological material, particularly if it is still alive, is variable in itself and in its response to both deliberate stimuli and to the environment.

In order to overcome the problems which arise from variability three basic principles need to be observed:

(1) control,
(2) replication,
(3) randomization.

Control

The word 'control' is used in two contexts in experiments. The first meaning is the standard, or normal treatment of the experiment and is the norm against which the other treatments are to be compared. (Treatment here does not mean medical treatment, but a deliberate variant of the experimental conditions which is to be investigated, such as rate of feeding per day or level of a nutritional factor.) It is sometimes referred to as an 'untreated control'. The presence of an untreated control in feedingstuffs experiments is vital; otherwise there is no internal standard of performance against which the novel treatments can be compared. Instead they can only be compared with vague concepts, such as 'typical', or 'average' performance. As variations from time to time and place to place are so great, such comparisons are bound to be insensitive and usually inconclusive.

The other meaning of control is in the sense of control over experimental variability. This can be done in a number of ways, such as carrying out the

experiment in uniform conditions, by a systematic approach to experimental procedures and by using uniform stock. Uniformity of conditions is more easily achieved with intensive than with extensive husbandry. Modern houses for broilers or, more latterly, for pigs with a high standard of insulation and freedom from draughts are well suited to experimentation. The daily or weekly routine is also easy to carry out in a systematic way in intensive housing. Making sure that all the animals in a house are fed, watered and, where necessary, weighed or otherwise handled at about the same time helps to keep their progress uniform and improves the accuracy of the eventual comparisons.

The animals to be used should be the same breed, the same age and weight and from the same origin where possible. Where it is compatible with the objects of the experiment, using animals of the same sex reduces variability further. The search for uniformity should not be carried too far. Highly in-bred stock may be very uniform but may be so different in some respect from commercial animals that their reaction to treatment is untypical. The results then are of limited applicability and, though very accurate, not capable of useful generalization.

Replication

Replication, or the repetition of treatments on a number of subjects, has benefits in two separate ways. If a sample of five individuals is taken from a population they can be measured and their average (or arithmetic mean) calculated. This can be repeated for a number of samples and it will be observed that the averages show less variation than do the separate members. The larger the sample and hence the greater the number over which the average is calculated, the more likely it is that the average will be close to the overall mean of the original population. This effect, an ironing-out of the original variability, is often the most effective way of improving the expected accuracy of the experiment. The amount of replication, or repetition, will be discussed later.

The second advantage of replication is that it enables the internal variability of an experiment to be measured. If we want to be sure that an experimental effect has not occurred by chance, then we want to know how large the effects of chance may be. An internal measure of chance variability is likely to be the most sensitive to use because otherwise we would have to use broadly based, and probably larger, measures from external sources. Measuring the internal error of an experiment also enables the overall experimental technique to be monitored. If the errors in experiments from one house vary considerably from time to time or if they show a tendency to increase, then the husbandry of the unit or the experimental technique may need to be reviewed or the supervision of the site tightened up. The number of replicates required in a particular case is discussed below.

Randomization

The essence of randomization is that the allocation of treatments to subjects should be left to chance and not to the deliberate and systematic choice of the experimenter.

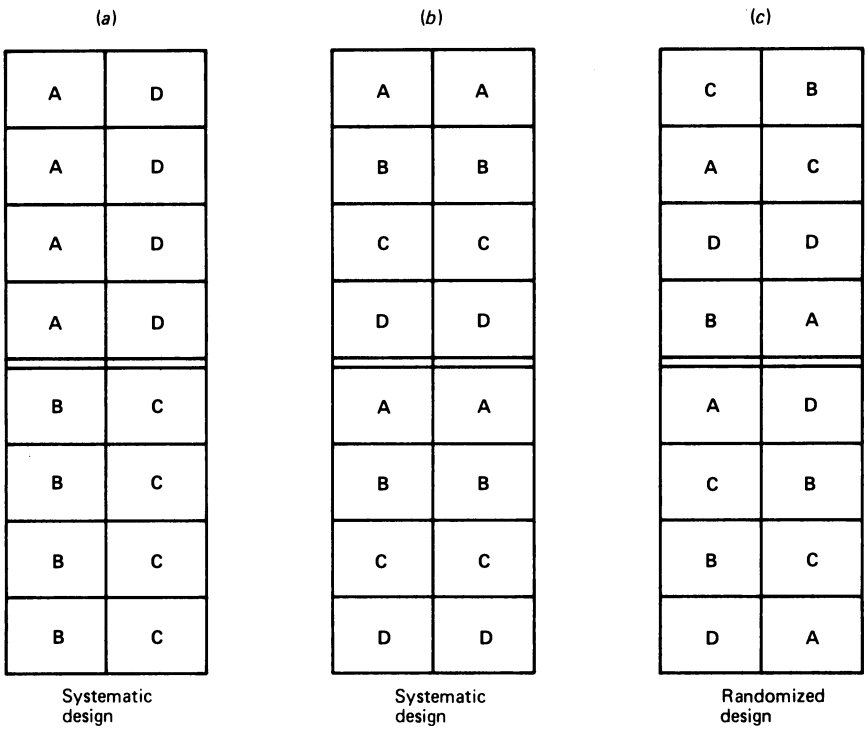

Figure 1.1 Examples of layouts

Figure 1.1 illustrates the difference between systematic and random designs. Suppose a broiler house has 16 pens, eight on each side and separated by a passageway. *Figure 1.1a* shows a design where the first four pens on the top left are given treatment A, the four pens on the bottom left, treatment B and so on. If the left hand side of the house is more favourable to animal performance, then treatments A and B would be favoured relative to treatments C and D; in statistical terms the comparison will be biased. *Figure 1.1b* is another systematic layout but here the disadvantage is less obvious. The treatments are spread out over the house, but the allocation is in the same order, A, B, C, D in each block or replicate. If there is a trend in the house in conditions, such as pens at the top being more favoured than pens lower down the house, then treatment A would be given the best conditions, followed by B, then C, with D having the worst conditions. Again the treatment comparisons are biased and, should differences be manifest, one cannot distinguish between treatment effects and effects due to pen position.

It is very easy to overcome these disadvantages. *Figure 1.1c* shows an example where the house is divided into blocks of four pens and the treatments are allocated randomly to the pens within each block. The random choice is carried out separately for each block, so the chances of any treatment being favoured or prejudiced are the same. The comparisons can then said to be unbiased. Not only can the experimenter be happy

that no bias has entered the comparisons but his results can be confidently reported as such.

The allocation at random needs to be the result of a mechanical process which allows the outcome to be entirely by chance. One method is to draw coloured or numbered tokens—this can be satisfactory if care is taken to ensure that the tokens are of the same weight, size and shape and that they are thoroughly shaken before drawing. A better way is to use random numbers either from tables of random numbers, as in Fisher and Yates (1974) or ones generated by a computer. The other merit of a randomized design is that it enables the experimental error to be validly estimated within the experiment. It follows then that the statistical analysis of the data, because it gives unbiased estimates of the treatment means as well as the experimental error, can also give valid tests of the comparisons between treatments.

Number of replicates

Probably the question most often asked of a statistician by an experimental scientist is, 'How many replicates do I need in my experiment to get statistical significance?'. Nearly always the statistician needs to have a lot more information before the answer can be given.

Figure 1.2 shows a histogram of the live weights of pigs in an experiment at the BOCM-Silcock farm at Barhill. The horizontal axis gives the range of the live weight of the animals while the vertical axis indicates the number of pigs falling in each range. The histogram has the shape typical of biological material with many subjects occurring in the middle of the range. There are fewer and fewer, the further one moves from the centre At the extreme weight there are only one or two animals in each range. The average of the 48 animals is at 62 kg near the highest category of the

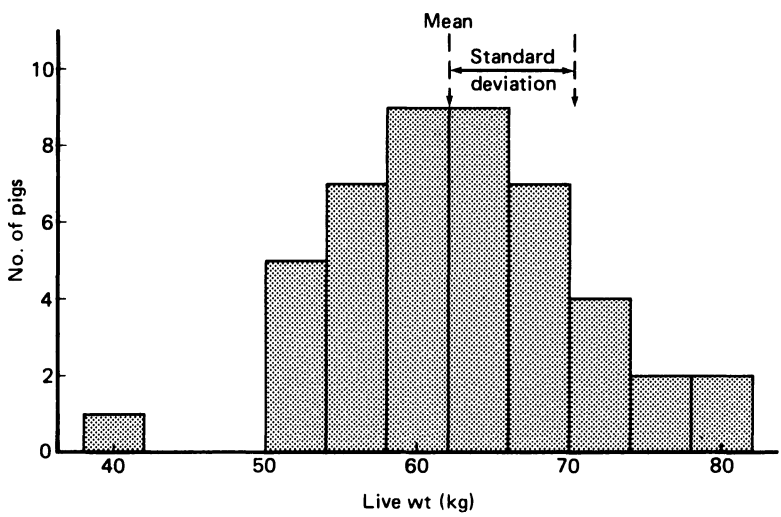

Figure 1.2 Histogram of live weights of pigs

histogram. The 'standard deviation' which measures the statistical variability of the animals is ±8.8, and is also shown on the diagram.

It can be shown that if the standard deviation per individual is s then the standard error of the mean of n individuals is given by:

$$\text{Standard error} = s/\sqrt{n} \tag{1}$$

The means of two treatments can be compared by the statistical test known as Student t-test. A convenient way of using this is to calculate the significant difference given by:

$$\text{Significant difference} = \frac{s\,t\sqrt{2}}{\sqrt{n}} \tag{2}$$

For example if an experiment in the house illustrated in *Figure 1.1* gave an experimental error of 5 units, then a significant difference (at the 0.05 level of probability) for comparisons of means of four pens would be:

$$\text{Significant difference (at } P = 0.05) = \frac{5.\ 2.26.\ \sqrt{2}}{\sqrt{4}} = \frac{5.\ 2.26.\ 1.414}{2} = 8.0$$

If eight rather than four pens were used for each treatment then the significant difference would be reduced to 5.6 units.

If d represents the significant difference, then equation (2) can be inverted to express n in terms of the other quantities, thus:

$$\sqrt{n} = \frac{s\,t\sqrt{2}}{d} \tag{3}$$

So if we want to plan an experiment and choose a suitable number of replicates, we must have available some indications of the quantities on the right hand side of equation (3). Thus to get a significant difference of a magnitude of 6 units in the house in question,

$$\sqrt{n} = \frac{5.\ 2.26.\ \sqrt{2}}{6} = 2.66$$

thus $n = 2.66^2$, i.e. approx. 7.

This approach therefore provides an estimate of the number of replicates required. However, there is a further dimension involved. Equation (3) illustrates how to obtain a significant difference of 6 units. If we are looking for a real effect (or difference between two treatments) of 6 units it would seem that this formula would be the answer. Unfortunately, the effect itself is liable to vary due to experimental conditions and the 'real' effect of 6 may be more or less on any particular occasion. The consequence of this is

that the calculated replication in the above example would give a 50% chance of detecting a difference of 6 units. Should one wish to be more certain of detecting the difference to allow for this variation the replication must be increased accordingly. It is necessary therefore to decide on the level of certainty of finding the difference: for example, this can be expressed as a 0.80 probability of detection (in other words, odds of 4 to 1 in favour of detecting the difference).

In summary, therefore, the items of information required to decide on the appropriate number of replicates in a planned experiment are:

Table 1.1 NO. OF REPLICATES REQUIRED TO DETECT A DIFFERENCE BETWEEN TREATMENTS (SIGNIFICANCE LEVEL 0.05)

Difference to be detected (expressed as % of mean)	*Probability of detection* 0.9	0.8	0.5
Coefficient of variation 2%			
2%	23	17	9
3%	11	9	5
4%	7	6	4
5%	5	4	
6%	4	4	
7%	4	3	
8%	3		
Coefficient of variation 4%			
2%	86	64	32
3%	39	29	15
4%	23	17	9
5%	16	12	7
6%	11	9	5
7%	8	6	4
8%	7	6	4
9%	6	5	
10%	5	4	
11%	4	4	
12%	4	4	
15%	3		
Coefficient of variation 6%			
2%			87
3%	86	64	32
4%	44	34	17
5%	34	26	14
6%	23	17	9
7%	16	12	7
8%	14	11	6
9%	11	9	5
10%	9	7	4
11%	8	6	4
12%	7	6	4
15%	5	4	
20%	4	3	
25%	3		

Difference to be detected (expressed as % of mean)	*Probability of detection* 0.9	0.8	0.5
Coefficient of variation 8%			
2%			124
3%		100	50
4%	86	64	32
5%	60	45	23
6%	39	29	15
7%	27	21	11
8%	23	17	9
9%	19	14	8
10%	16	12	7
11%	12	10	6
12%	11	9	5
15%	7	6	4
20%	5	4	
25%	4	4	
30%	3		
Coefficient of variation 10%			
3%			87
4%		100	50
5%	86	64	32
6%	60	45	23
7%	44	34	17
8%	34	26	14
9%	27	21	11
10%	23	17	9
11%	19	14	8
12%	16	12	7
15%	11	9	5
20%	7	6	4
25%	5	4	
30%	4	4	
35%	4	3	
40%	3		

(1) the size of the difference which is required to be detected,
(2) the size of the standard deviation for experimental error in the unit concerned,
(3) the level of probability of detection of the difference, if it is real.

Table 1.1 gives the replication appropriate to a number of alternative variations of these quantities. In this table both the size of the required difference and the standard deviation are expressed as percentages of the mean. (When the standard deviation is so expressed it is known as the 'coefficient of variation'.) This table is derived from Table E in Davies (1954).

Let us assume, for example, that an experiment is to be carried out on the live weight gain of turkeys, where the coefficient of variation per pen is expected to be 4%. The experimenter wants to be able to detect a difference of 6%, needs to be reasonably certain of detecting this and so chooses a level of probability of 0.8. The table shows that he will need a replication of nine pens on each treatment. This same number of replicates per treatment will also give a probability of 0.5 of detecting a real difference of 4%.

Magnitude of experimental errors

Table 1.1 gives a way of calculating the required replication when the standard deviation (or coefficient of variation) and the difference to be detected are known. When designing experiments it is therefore useful to know how big the coefficient of variation is likely to be. Experiments carried out on BOCM-Silcock and other Unilever farms for many years provide estimates of typical coefficients of variation for various stock. These are given in *Table 1.2*. In addition, Roberts *et al.* (1978) and Rosen, Roberts and Widdowson (1978) have carried out surveys of published research results and the experimental errors recorded in those surveys were not dissimilar to those given in *Table 1.2*.

Table 1.2 TYPICAL COEFFICIENTS OF VARIATION OBSERVED IN ANIMAL EXPERIMENTS

Broilers (live weight, 8 or 9 weeks)	2.5% per pen of 100 birds
Turkeys (live weight, 12 to 16 weeks)	1–2% per pen of 60–150 birds
Pigs (rate of gain from weaning to 90 kg live weight)	10% per pig
Calves (live weight, 12 weeks)	10% per calf
Laying hens (eggs/100 hen-days)	3–6% per unit of 50–60 hens
Dairy cows[a] (whole or part lactation yield)	10–25% per cow

[a]Not change-over trials

Number of animals per experimental unit

When experiments are carried out using large animals, calves, pigs or cattle, then it is often appropriate to use the individual animal as the experimental unit. This is straightforward if they are penned separately. Although pigs are often penned in groups, keeping separate records for each animal is possible if individual feeders are used. On the other hand,

poultry are usually kept in flocks in commercial houses and a problem arises as to the preferred number of birds in each experimental unit. It is not very practicable to use individual birds as units, partly because it is wasteful of resources and partly because individual bird behaviour and micro-environment may be untypical. At the other extreme, very large houses of 1000 or more birds introduce too much risk of environmental variation. The optimum size is given when the number of birds per pen is large enough to reduce bird to bird variability to a low level compared to differences between pens. There is little point in analysing the optimum level in too sophisticated a way as there is little to choose between numbers in the range from 50 to 100 birds per pen. Accordingly a number in that range can be chosen with the final decision resting on practical considerations, such as a convenient number for feeding.

Some trials have been carried out in the past with cages holding as few as six broilers or sub-divisions of broiler houses holding as many as 2000. The small cages took quite a high level of resources, but the results were usually too variable to give helpful conclusions in nutritional work. At the other extreme in the large houses, the bird to bird variation was virtually eliminated but it was rarely possible to have more than two pen replicates per treatment; when inexplicable results occurred it was not clear whether a large nutritional effect had arisen or whether there had been a mistake in the records due to the logistic problems of handling so many birds.

The unit sizes given in *Table 1.2* are ones which have been found to give good results and satisfy the reasoning given above. As mentioned, the actual number decided on per pen may depend on physical factors, such as modules of a convenient size within a house. The convenient unit for battery hens may be a row of cages sharing a mechanical feeder: if there are 36 cages in the row with two hens a cage then the resulting number of 72 birds is satisfactory and falls well within the range of 50 to 100 birds discussed earlier.

Number of pens per house

The growth of nutrition as an experimental science has given rise to trials of increasing complexity, including multifactorial designs and exploration of response equations. A large number of pens in a house facilitates such experiments. A number which is a multiple of 12 gives a high degree of flexibility and factors with levels of 2, 3, 4 and 6 can then be used. Thus, houses with 48, 60, 72 or 96 pens are particularly useful and can accommodate even quite complex experiments with generous replication.

Conclusions

The topics discussed in this chapter are those which are particularly relevant to nutritional experiments in the feedingstuffs industry. It is not possible here to cover more than a small part of the statistical planning and design of experiments. This now has a considerable literature and should be consulted for further information. The classic text of Cochran and Cox

(1957) is still very useful to biometricians, and that of Davies (1954) is of more general relevance than is implied by the title. One other text which should be specially mentioned is that by Cox (1966), which contains advice on the organization of experiments not easily available elsewhere.

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2

THE INTERPRETATION OF RESPONSE DATA FROM ANIMAL FEEDING TRIALS

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Many animal feeding trials are conducted every year in universities and research institutes and on feed manufacturers' research farms, both in the UK and elsewhere in the world. Some of the data eventually get published. In view of the large investment in this activity it is surprising how little has been written about the methodology of interpreting such experiments. There are a few recent papers (e.g. Lerman and Bie, 1975; Robbins, Norton and Baker, 1979; Heady, Guinan and Balloun, 1980; Ware *et al.*, 1980) but most of those who carry responsibility for nutritional trials either use their own preferred method to interpret data (which, though lacking a logical foundation, often produce wise judgements) or hand the results over to a professional statistician for analysis. The statistician applies rigorous logic but does not always arrive at appropriate conclusions. The worst conclusions of all are apt to be drawn by graduate students, who write most of the papers that eventually get published and who lack both the wise judgement of the experienced feed formulator and the extensive skills of the professional statistician. Thus it comes about that many dose/response trials are interpreted with the aid of nothing more elaborate than a Student's t-test or a multiple range test, which is rather like trying to peel an apple with an axe.

Before proceeding to the main discussion of how response data should be interpreted, there are some important assumptions to be made. Firstly, we will assume that the data come from trials which are properly designed and adequately replicated. These matters are discussed in the other two chapters in this section and will not be reviewed again here. Nevertheless, it is important to understand that many nutritional trials have too few treatments or too few replicates to give any hope of answering the question for which they were designed. Secondly, we will assume that thought has been given to the scales used for measuring inputs and responses. For example, trials investigating amino acid responses in *ad-libitum* fed animals may make more sense if the intake of the limiting amino acid is plotted on the abscissa, rather than the dietary concentration of that amino acid; trials with dairy cows may make more sense if energy output (calculated from

milk yield and composition and liveweight changes) is taken as the response criterion, rather than the volume of milk. The choice of appropriate scales is an important matter, but further discussion of it is beyond the scope of this chapter. Thirdly, we will assume that nobody is trying to estimate 'the requirement' for a nutrient. This is not because requirements are known, but because the term 'requirement' is unhelpful. What the practical nutritionist needs to know is the rate at which animals in a given class, in a reasonably well-defined nutritional and environmental context, will respond to incremental inputs of a given nutrient. Armed with this information, and a knowledge of his marginal costs and the value of extra output, he can calculate an optimum dose.

To illustrate the point that the method of analysing results can make a large difference to the conclusions drawn, let us consider some data from a

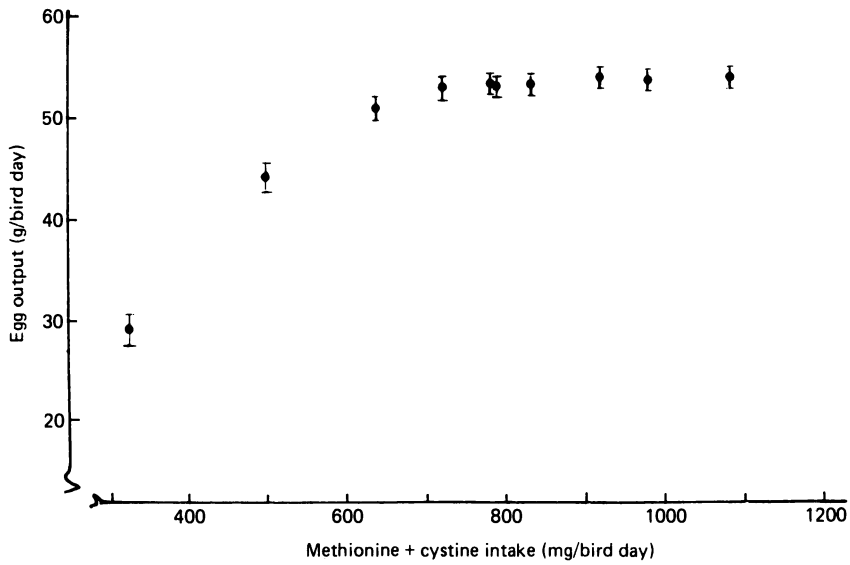

Figure 2.1 Data from an experiment reported by Morris and Blackburn (1982), in which laying pullets were fed from 30 to 40 weeks of age on diets of varying protein content (methionine being the first limiting amino acid in the protein mixture used). The data plotted are means with standard errors, taken from the last four weeks of the trial

recently published chicken experiment, as reproduced in *Figure 2.1*. This was a well-replicated trial (54 groups of 72 laying pullets) with ten dietary treatments. The data are therefore more precise and more wide-ranging than the results of most animal feeding trials and, whatever problems may arise in interpretation, they cannot be blamed on the use of inadequate resources. We will consider in turn a number of procedures which are commonly used to interpret results such as those in *Figure 2.1*.

Duncan's multiple range test

If one compares treatment means with the aid of a standard error calculated from replicate groups (there were three replicate groups of 72

pullets allocated to the two lowest treatments and six replicates for each of the remaining treatments), diets 1, 2 and 3 all differ significantly, but there are no significant differences ($P = 0.05$) between diet 3 and any of the remaining treatments. This conclusion is reached whether one uses a variance ratio (F test) or a multiple range test (such as that due to Duncan, 1955). This method of handling data has been used more commonly than any other in the literature (and especially so in the USA) and it is wrong for two reasons. Firstly, the comparison of treatments by means of a multiple range test is inappropriate when there is a logical structure to the set of treatments. Secondly, the use of a conventional 5% probability value is inappropriate when trying to obtain the best estimate of some end point, as opposed to requiring a high degree of confidence that we have not gone too far along some input scale. For example, if we can show that the odds are 5:1 that by spending another £1 on *dl*-methionine we can get back another £2 worth of eggs, it would be foolish to conclude that we should not spend the £1, because the odds in our favour are less than 20:1. The conventional 5% probability level is akin to a judgement made in a criminal trial when an issue has to be proved 'beyond reasonable doubt'. In making judgements about the optimum input of a nutrient we need something more akin to the 'balance of probability' argument which is used when apportioning liability in a civil suit. Since these are well worn arguments to the professional statistician, and he would immediately counsel some form of regression analysis for an input/output trial such as *Figure 2.1*, it is surprising that so many papers have been published in which Duncan's multiple range test has been used to support false conclusions.

The bent stick

Numerous authors have used simple regression analysis to interpret their data. The commonest procedure is to assume that response is a linear

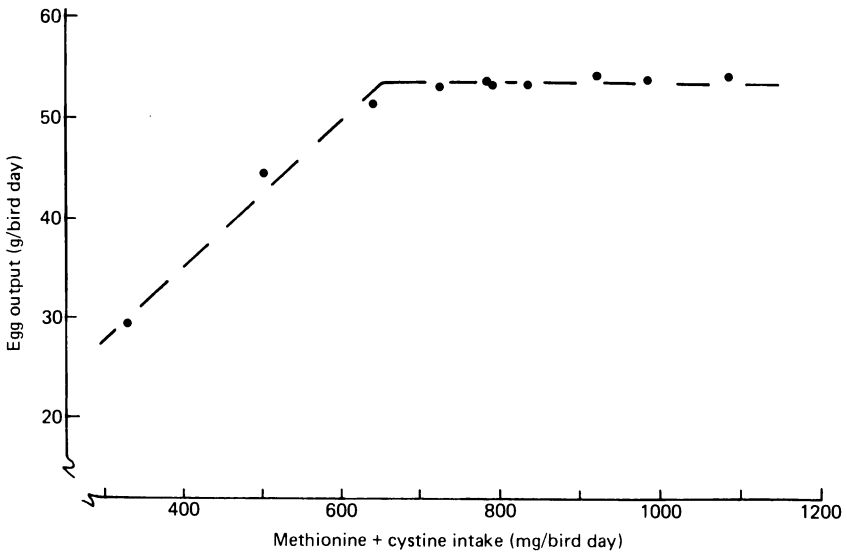

Figure 2.2 The data from *Figure 2.1*, with a 'bent-stick' model fitted by minimizing the residual sum of squares

function of input up to some threshold value, at which the response abruptly ceases. This 'bent-stick' model is fitted to the data of Morris and Blackburn (1982) in *Figure 2.2*. The model is a good fit to the data, the deviation's mean square being slightly less than the error mean square calculated from replicate groups. However, it is a simple matter to show that this particular model always leads to false deductions about the optimum input.

Suppose, for the sake of argument, that an individual animal shows an input/output response exactly corresponding to the bent stick model. This is not an unreasonable proposition and is exactly the assumption made when nutrient requirements are calculated in the familiar factorial way:

$$y = aW + bP$$

where y is a nutrient requirement, aW is a maintenance allowance proportional to body weight (W) and bP is a production allowance proportional to the output (P) of the individual animal. Note that the model cannot be tested, since one cannot measure the output of milk or eggs or weight gain from the same animal under the same physiological conditions at enough different input levels to allow precise definition of the shape of the individual response relationship. However, if we suppose that

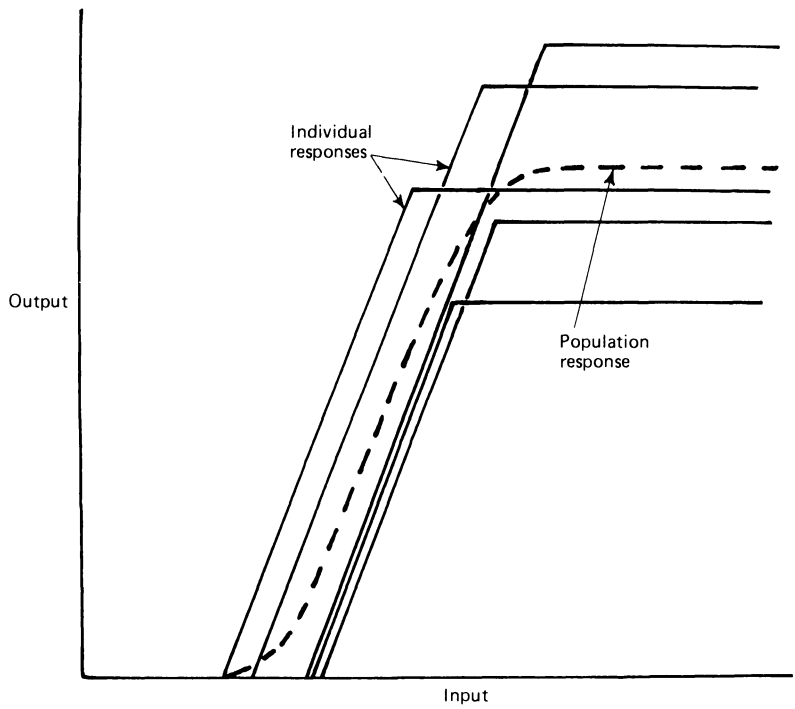

Figure 2.3 The input–output relationship for a population of animals, where individual responses conform to a bent-stick model, but individuals vary in their productive potential and in their maintenance requirement. In the case illustrated, individuals do not vary in their net efficiency of nutrient utilization for production, as indicated by the slope of the response lines

the model is reasonable and applies to all individuals in a population, but that those individuals vary (as they must) in W and P, then we have the situation shown in *Figure 2.3*. The integration of a set of bent stick responses, where there is variation in individual maximum response levels, necessarily produces a curve showing diminishing returns to increasing inputs and reaching a plateau at the point where the individual with the highest requirement ceases to respond. Notice that *Figure 2.3* is drawn without supposing that individuals vary in their net efficiencies of nutrient utilization for production. There may be some variation amongst individuals in net efficiency (it is very hard to tell) but the proposition of curvilinearity in the population response rests solely on the incontrovertible statement that individuals vary in size (and therefore in maintenance requirements) and in productive potential. There is a special set of conditions under which all the bent sticks in a population would turn at the same input value (when the correlation of P with W is -1.0 and the standard deviations of P and W are in the ratio $b{:}a$) but these conditions will not occur in practice. Therefore, in any feeding trial in which more than one animal has been used, the real response function must be curvilinear and will show diminishing returns.

The consequences of fitting a bent stick model to a set of experimental data is almost always to underestimate the optimum dose. In *Figure 2.2*, the model suggests an optimum input of 650 mg methionine plus cystine (M + C) per day, but profitable responses are continuing well beyond that point. Although a bent stick model may, in a particular case, be a good fit in the statistical sense it is always a bad fit philosophically and for practical purposes.

The parabola

By fitting the model

$$y = a + bx + cx^2$$

where x is input and y is response, one can often obtain a curve which fits the data well. *Figure 2.4* shows the same results as *Figures 2.1* and *2.2*, but this time with two parabolic curves superimposed. Curve 1 is fitted to the data for all ten diets and reaches a maximum at 900 mg M + C per day. Some users would adopt this as their estimate of requirement. Others would calculate the cost of methionine and the value of eggs and, if these were £2/kg and 50p/kg respectively, would derive an optimum input of 886 mg M + C per day.

One difficulty with a parabolic curve is that it predicts a reduction of output beyond the optimum dose. This may not be of concern to particular users in particular contexts, but it is not in accord with the evidence for most nutrients and it can lead to serious trouble when incorporating the equations into computer prediction models. Many nutrients do cause a reduction in output when fed to excess, but the response curve is seldom symmetrical. More typically, there is a substantial range within which a

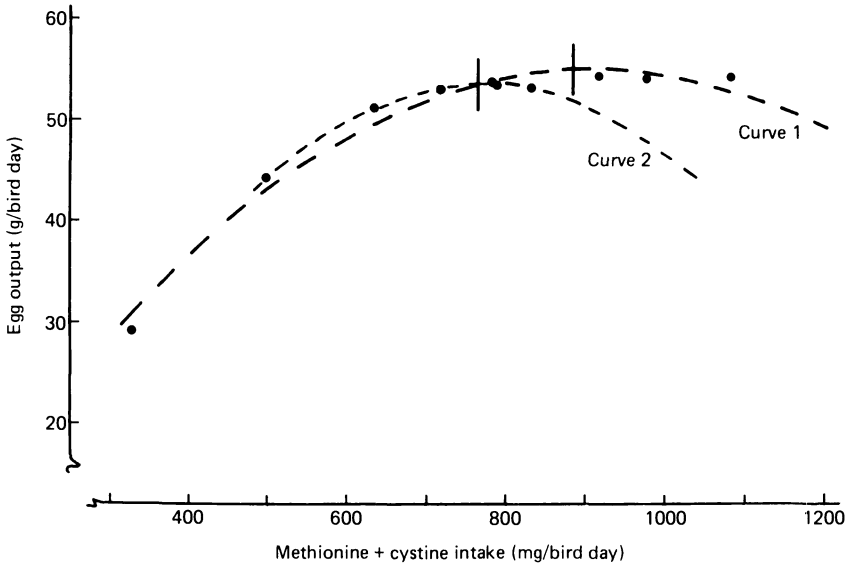

Figure 2.4 Parabolic models fitted to the data of *Figure 2.1*. Curve 1 uses all the experimental values and reaches a maximum at 900 mg input. The optimum input of methionine plus cystine is 886 mg/day, assuming a cost of £2/kg for methionine and a value of 50p/kg for egg output. Curve 2 is fitted to six of the ten treatment means and leads to an estimated optimum input of 759 mg methionine plus cystine per bird day

nutrient can be in surplus without causing any adverse effects on performance. This is illustrated by the experiment shown in *Figure 2.1* in which M + C was increased by varying the protein content of the diet, *not* by adding free methionine.

By choosing a restricted range of diets, the experimenter can usually obtain data which fit a parabolic curve rather well and avoid the problems of an extended plateau. This is often used as an argument to justify the model, but it is a dangerous argument. It presupposes that the experimenter has a good idea where the optimum input will lie (he usually does) and that the slope of the curve in this region can be best estimated by spacing the treatments closely about this assumed optimum input. Unfortunately, the shape of a fitted quadratic curve is very sensitive to the range of input values selected. This is illustrated by curve 2 in *Figure 2.4*, which is fitted to six of the ten treatments (still a larger experiment than most) and gives an estimated maximum output at 776 mg M + C per day and an optimum input (for the prices given above) of 759 mg M + C per day. Curve 2 is an excellent fit to the restricted set of data, but the estimate of optimum input is only 85% of the estimate obtained with the full set of data.

The parabolic model is thus philosophically wrong, in that it presumes symmetrical responses to deficiency and excess, with no intervening plateau. It is practically dangerous because it is apt to fit a limited set of data rather well and, in so doing, fails to give the experimenter any warning that his conclusions could be quickly falsified by another experiment. If he has taken the precaution of conducting a number of experiments before drawing any conclusions, he will be faced with the problem

that curves fitted independently to each trial cannot be reconciled by pooling the coefficients of the quadratic equations; nor can the data be pooled to produce a single equation if the maximum output levels vary appreciably in the several trials.

The hyperbola (exponential and inverse polynomial models)

These models are asymptotic in form and so incorporate the notion that, within the range of interest, the output response rises towards a plateau and does not diminish again at high input values.

Various exponential equations have been used, a simple form being:

$$y = a - bC^{-x}$$

where y is the output, x is the input and a is the maximum value of output towards which the curve is proceeding.

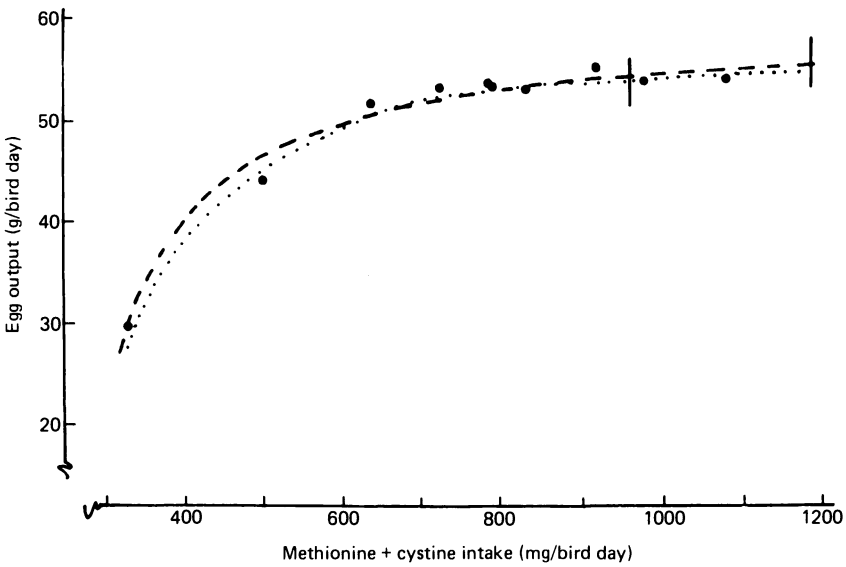

Figure 2.5 Exponential (· · · · ·) and inverse polynomial (– – –) models fitted to the Morris and Blackburn data. Taking prices of £2/kg for methionine and 50p/kg for eggs, the estimates of optimum input are 1184 mg/day for the inverse polynomial curve and 964 mg/day for the exponential

The inverse polynomial models were introduced by Nelder (1966) and a particular form is described by Morris and Blackburn (1982) as applicable to the data of their experiment. Curves derived from these two models are shown in *Figure 2.5*, again using the same set of data as in *Figures 2.1, 2.2* and *2.4*.

Both curves are a satisfactory fit, as judged by the residual mean square, but they round off the 'corner' of the response in a rather unsatisfactory way, which makes the user rightly suspicious. The curves also predict continued small responses in a region where it is very doubtful whether any

response is occurring and thus they both regularly overestimate the optimum dose. This is particularly true when dealing with an input, such as methionine or an antibiotic, whose marginal cost is rather small in relation to the value of the output, so that the economic optimum is close to the true maximum yield. With more expensive inputs, such as biotin or tryptophan, a hyperbolic function will sometimes lead to a satisfactory estimate of optimum dose.

An advantage of these models, in comparison with the parabola, is that, in both cases, the coefficients of the equations are estimates of meaningful biological parameters, such as maximum output or rate of decline in output, and it is thus possible to calculate response curves for populations with output characteristics differing from those observed in the experiment. However, the tendency of these functions to overestimate the optimum dose is a serious flaw.

One temptation which must be resisted at all costs, is to fit an asymptotic model to experimental data and then to choose some arbitrary proportion of maximum output (e.g. 95%) as the 'requirement' (e.g. D'Mello and Lewis, 1970). If the model is appropriate, then the user should be given the equation of the model so that he can determine his own optimum for a local set of prices.

The Reading model

Fisher, Morris and Jennings (1973) have described a model which starts with the assumption that an individual animal responds in a bent-stick fashion (as in *Figure 2.2*). From this postulate, a population curve is constructed (as in *Figure 2.3*), based on information about the standard deviations of body weight and output. The equations needed to fit the model to a set of experimental data have been given by Curnow (1973) and examples of its application to laying hens have been published for lysine (Pilbrow and Morris, 1974) and tryptophan (Morris and Wethli, 1978). Fisher (1981) and Clark, Gous and Morris (1982) have used the model to describe responses of growing birds to amino acid intake.

Figure 2.6 shows the Reading model fitted to the same set of data as was given in *Figures 2.1, 2.2, 2.4* and *2.5*. The model is a good fit (though not significantly better than any of the alternatives discussed previously). One advantage of the Reading model is that its curvature depends upon the variability of the experimental animals, which does not change much from trial to trial, and is independent of the choice of dietary treatments. Thus, a Reading model fitted to the data from treatments 2 to 7 only, gives essentially the same curve and so leads to the same conclusion about optimum dose as the full data. This is in marked contrast to the results of fitting quadratic equations to sub-sets of the data.

Another advantage of the Reading model is that the coefficients of the response equation are meaningful numbers, being the net efficiencies of nutrient utilization for maintenance and for production. Three consequences flow from this. Firstly, given a set of experimental data for animals with particular productive characteristics, one can reasonably extrapolate to make an estimate of the response curve for another group of animals of

different mean body size or with different potential output. Secondly, given the results of a number of experiments one can pool them to obtain best estimates of the response coefficients for future use. Thirdly, one can estimate net efficiencies by procedures other than a simple feeding trial and so obtain independent confirmation of the response coefficients.

The major disadvantages of the Reading model are that it assumes that outputs of individual animals are normally distributed about the mean and it requires a meaningful estimate of mean body size. These conditions are usually satisfied in short-term trials, but in long-term egg production or milk production experiments individual yields are not normally distributed

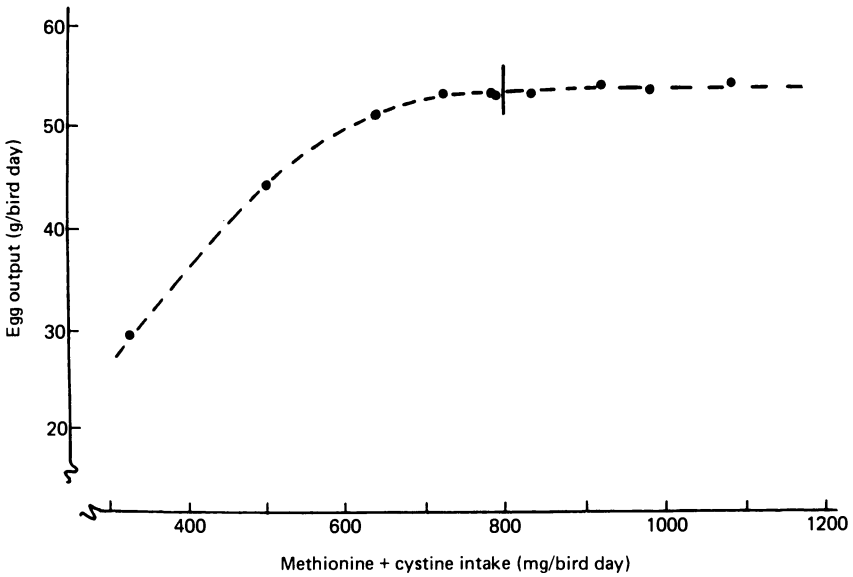

Figure 2.6 The Reading model fitted to the Morris and Blackburn data. The underlying assumption is that individual birds have a methionine + cystine requirement (M + C) defined by M + C = 13.04W + 10.15E, where W = body weight (kg) and E = egg output (g/bird day). The population response curve is then derived, by assuming normal variation in E and W and integrating individual response lines, as illustrated in *Figure 2.3*. Using the model, the estimated optimum input is 794 mg/day

about the mean; and in long-term growth trials mean body size changes during the course of the trial. A modification of the Reading model to cope with non-normal distributions is theoretically possible, but no suitable computer program is yet available for this.

Some animal feeding trials cannot be interpreted with the aid of a Reading model, either because the input scale is complex or ill-defined (e.g. a comparison of feeding programmes) or because the measured output does not depend directly on the input variable (e.g. measuring liveweight changes where body composition is variable and the real response parameters are protein deposition and fat deposition). Empirical solutions can sometimes be found for these problems by fitting one of the curvilinear models described above. However, a real understanding of dose–response relationships and ability to predict responses in future

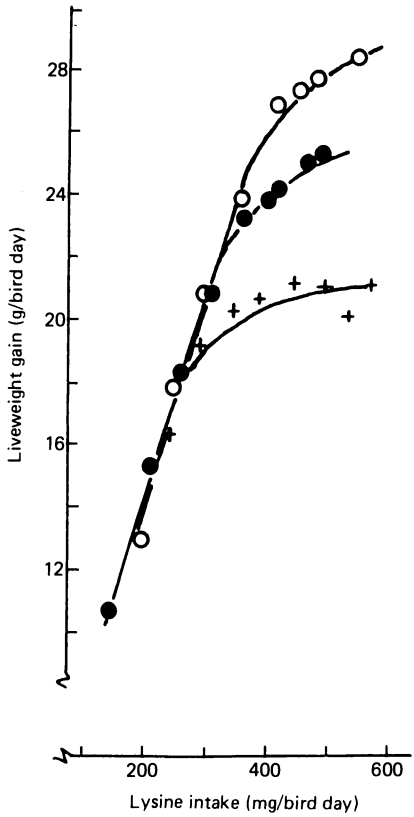

Figure 2.7 Results from Clark, Gous and Morris (1982) showing the application of the Reading model to chick growth data. The curves represent three separate experiments, but all are derived from the simple model that the lysine intake (L, mg/bird day) required by an individual chicken is given by $L = 0.03W + 12.94\Delta W$, where W is mean live weight (g) and ΔW is the rate of liveweight gain (g/bird day)

situations depends upon reformulating the problem in more fundamental biological terms and then building a simulation model which incorporates the necessary information.

The fact that a large computer is needed to fit a Reading model has not so far proved a barrier to its use to interpret suitable sets of data. The user of the output from the model does not need a computer to calculate optimum doses for his local prices, since a set of tables can be prepared giving optimum inputs for various cost ratios (*see*, for example, Morris and Wethli, 1978).

The Reading model was originally developed to help in the interpretation of input–output experiments involving laying hens fed on diets limiting in particular essential amino acids. However, the underlying concept, that organisms are variable and therefore the essential problem is to determine what proportion of a population shall be supplied with non-limiting levels of a nutrient, is applicable to nutrients other than amino acids and to species other than chickens. It seems equally applicable to the problems of optimizing fertilizer application to fields of wheat. *Figure 2.7*

shows an example of the use of a Reading model to reconcile data from three growth trials. The curves fit the data quite well even though the maximum growth rates differed in the three trials and, since they derive from a single equation, it seems reasonable to suppose that one could predict the response curve for a flock of chickens with a much higher growth rate, if that were required.

Conclusions

It is always wrong to use either a multiple range test or linear regression to interpret the results of a dose–response trial, where the ultimate objective is to arrive at an estimate of optimum dose. Some form of curvilinear analysis is required. A parabolic curve will often give a good fit to experimental data, but this may give a false sense of security, since the shape of a fitted parabolic curve is unduly sensitive to the range of treatments selected. Inverse polynomial and exponential functions give asymptotic curves which sometimes fit well, but are apt to predict continuing economic responses at high inputs where the real response has ceased. The Reading model has a curvature which is largely independent of the choice of treatments and it therefore gives realistic estimates of optimum dose even when the data are scanty. It also readily allows the combination of evidence from trials with disparate levels of performance and is suitable for extrapolation to levels of performance which lie outside the range of experimental data.

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3

ERRORS IN MEASUREMENT AND THEIR IMPORTANCE IN ANIMAL NUTRITION

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As an introduction to this chapter it is desirable to explain what is meant by the word 'error'. In reference tables it is common to find a single figure quoted for some biological quantity, representing a typical value. For example, in Technical Bulletin 33 (MAFF, DAFS, DANI, 1975) the crude protein content of barley grain is given as 10.8% of the dry matter. Clearly, not all samples of barley will contain precisely 10.8% protein. There are many reasons why this should be so: major differences in the varieties or

Table 3.1 ORDERED ME ESTIMATES FROM 20 SAMPLES OF A BATCH OF BARLEY AND 20 SAMPLES OF A BATCH OF HAY (MJ ME/kg DM)

	Barley	*Hay*
	10.5	7.5
	10.8	7.6
	11.0	7.8
	11.2	7.9
	11.3	8.0
	11.4	8.1
	11.9	8.2
	12.3	8.5
	12.5	8.6
	12.5	8.9
	12.5	9.0
	12.8	9.1
	13.0	9.2
	13.2	9.4
	13.4	9.7
	13.5	9.8
	13.7	10.2
	13.8	10.6
	14.3	10.8
	14.4	11.1
Mean	12.5	9.0
Standard deviation	1.18	1.09

growing conditions, variation in the samples taken even within the same batch, and so on. Variation in a recorded value may also be partly due to small changes in the chemical technique, or due to the way the analyst uses the equipment. In statistics, this variability is usually termed the 'error', since it is a measure of the difference between a single observed value and the mean of all possible values in a population.

The three types of variation mentioned above would be termed biological error, sampling error and analytical error, the last two being measurement errors. The term 'error' does not imply that mistakes have been made, although these could form part of it. In this chapter the size and possible consequences of errors in measurement, and particularly of chemical analysis, associated with animal feeding are considered.

It is necessary to consider what happens to the error when data are combined. For example, the data in *Table 3.1* are the ME values for 20 samples from a batch of barley and 20 from a batch of hay. The mean for the barley is 12.5 MJ/kg DM and for the hay 9.0 MJ/kg DM. The table shows that the individual sample values vary quite considerably; this variability is measured by the respective estimated standard deviations of 1.18 MJ/kg DM and 1.09 MJ/kg DM. If the intention were to feed the hay and barley to cattle to provide a daily intake of 50 MJ, the following ration on a fresh weight basis might be suggested:

	Fresh weight (kg)	*Dry matter content* (g/kg DM)	*DM intake* (kg)	*Total ME supplied* (MJ)
Hay	4.1	870	3.57	32.1
Barley	1.7	840	1.43	17.9
			5.00	50.0

The error associated with this figure on a DM basis is calculated as the square root of the sum of the variances × (intake levels)^2, thus

$$\text{Error in total} = \sqrt{(4.1 \times 0.87 \times 1.09)^2 + (1.7 \times 0.84 \times 1.18)^2} = 4.24 \text{ MJ}$$

This illustrates that the errors do not cancel each other out although the error per kg DM of the feeds combined (standard deviation = 4.24/5 = 0.85 MJ/kg DM) would be smaller than the error per kg DM of the individual two constituents. A reduction in the error associated with a single constituent will therefore reduce the total error. The apparently smaller error per kg DM of the combined feed can lead to a false sense of security, since it must be remembered that mixing feed ingredients can itself result in additional errors not included in the calculation.

The job of the nutritionist is to plan how animals should be fed. This is done by balancing animal requirements with feeds. If this is to be done with any degree of precision, knowledge is needed of

(1) nutrient requirements,

(2) nutrient value of feeds, and
(3) interaction between feeds.

Nutrient requirements may be obtained by measuring the response to a known amount, or set of amounts, of input, or by determining the requirements for the various components of performance separately and then adding them together. Thus, there is a heavy reliance on the knowledge of the composition of feeds and body tissues.

Nutrient requirements as given in tables are mostly average values and appear to take no account of variability between animals. Generally, the written material accompanying the tables discusses such variability, but this is not always read by the users. Rigid adherence to tables would therefore mean that some animals would be underfed and some overfed. To reduce the number of animals that might be underfed, Technical Bulletin 33 (MAFF, DAFS, DANI, 1975) adds a 5% safety margin to their requirement equations. There is no firm statistical basis for this but it does have the effect of pushing the mean requirements up, decreasing the chances of underfeeding some animals at the expense of increasing the chances of overfeeding others. This argument is less easy to apply to animals fed *ad libitum* where increases in a nutrient level to form a 'safety margin' may reduce feed intake, thereby leading to little change in consumption of the nutrient.

The nutritionist also needs an estimate of the nutritional values of the feeds available. Such estimates may be based on experience, tables of feedstuffs composition, or chemical analysis used either directly (e.g. Ca) or indirectly (e.g. MAD Fibre to predict ME). Each of these approaches is affected by both variation in the raw material and analytical and sampling error. Samples taken without due care show great variation, but this is not inevitable. For example, six silos were each filled in a short period (about a week), with silage from a single cut. Five samples were taken at monthly intervals as part of a study of feed intakes carried out by ADAS Nutrition Chemists at Leeds. The silage samples were chemically analysed for DM%, CP% and MADF% as shown in *Table 3.2* (Hopkins, 1980 personal communication), and the data indicate that the SDs associated with each of the means are typically 3–6% of the mean. Guidance on sampling to minimize error is available from MAFF (MAFF, 1977, 1982b).

The error involved in using standard tables of feed ingredient composition can be illustrated by a simple example in which a compound is formulated to contain 160 g/kg crude protein, using just two ingredients,

Table 3.2 VARIATION BETWEEN SAMPLES OF SILAGE FROM THE SAME CLAMPS

Clamp	*Replication*	*Mean* DM%	*SD*	*Mean* CP%	*SD*	*Mean MADF %*	*SD*
1	5	26.7	0.85	17.7	1.01	33.8	0.32
2	5	33.8	1.01	16.8	0.64	36.2	1.79
3	5	24.6	0.94	16.6	0.88	36.5	0.82
4	5	22.2	0.75	16.9	0.41	38.6	0.55
5	5	18.0	1.31	15.2	0.97	39.8	1.63
6	5	23.0	1.25	18.6	0.41	33.4	1.15

(From Hopkins, J., personal communication)

barley and extracted soya bean meal. Values from Technical Bulletin 33 (MAFF, DAFS, DANI, 1975) for the dry matter and crude protein contents of these two feeds are:

	DM (g/kg)	*CP* (g/kg DM)
Barley	860	108
Extracted soya	900	503

Using these values, a compound containing 160 g crude protein/kg DM could be obtained by mixing 81.4% barley and 18.6% soya. If this is compared with a combination which might be reached by approximation (say 80% barley, 20% soya), there is an apparent increase in precision. However, had different tables of composition been used, a different formulation would have been obtained. Furthermore, it must be remembered that there is variability associated with each of the tabulated values. If the dry matter of the two feeds actually used were 850 g/kg and 870 g/kg respectively, the compound containing 81.4% barley and 18.6% soya would contain only 156 g crude protein/kg DM while that of the approximate formulation would contain 161 g/kg DM, compared to the desired formulation of 160 g/kg DM. The variation in the dry matter content of the two particular raw materials is likely to be small, but the same is not true for their protein contents. *Table 3.3*, for example, provides data which

Table 3.3 CRUDE PROTEIN CONTENT OF BARLEY AND SOYA FROM ANALYSIS DURING JAN–JUNE IN TWO YEARS

		No. of samples	*Mean CP %*	*SD*
1981	Soya	796	43.85	1.66
	Barley	739	11.06	1.19
1982	Soya	834	43.24	1.79
	Barley	226	10.80	1.31

(From Dalgety Spillers Ltd, personal communication)

Table 3.4 PROTEIN CONTENT (g/kg) OF A COMBINATION OF BARLEY AND SOYA USING THE EXTREMES GIVEN BY MEAN ±2 SD FROM *TABLE 3.3* FOR 1982 SAMPLES

Barley value	*Soya value*	*Protein content* (g/kg)
Lowest	Lowest	140
Lowest	Highest	154
Highest	Lowest	185
Highest	Highest	196

indicate the extent of variation in the protein content of barley and soya in two successive years. Assuming normality of the distributions, approximately 95% of the values will lie within the range of the mean $\pm 2 \times$ SD. For the 1982 samples, the mean $\pm 2 \times$ SD gives the range 8.18–13.42% protein in barley and 39.66–46.82% in soya. The combinations of the upper and lower limits for each of these constituents, as shown in *Table 3.4*, give examples of how the protein contents of compounds could be well above or below the 160 g/kg DM expected, although the likelihood that these specific combinations will occur is less than 1 in 1000.

The limits of variation of the protein content of a compound feed, declared as containing 16% protein, permitted by the current UK Regulations are ± 10% of the declared value. These were set at approximately 2 × SD above or below the mean value. From February 1983, this will be changed (*see* The Feeding Stuffs Regulations 1982 (MAFF, 1982a)) to 10% below or 20% above the declared figure. The risk involved in producing a compound feed which falls outside the permitted legal limits of declared value, particularly when using average composition values from standard tables of nutritional data, can be quantified if it is assumed that the figures quoted for the protein content of barley and soya in Bulletin 33 (MAFF, DAFS, DANI, 1975) are subject to the same degree of between-batch variation as that illustrated in *Table 3.3*. Using the example quoted earlier of a compound with a declared protein content of 160 g/kg DM made by mixing barley and soya in the proportions of 81.4% and 18.6% respectively, then approximately 15% of such mixes are likely to fall outside of ± 10% of the declared value. This risk will decrease as the number of ingredients in the compound increases (*Table 3.5*), assuming that all

Table 3.5 EFFECT OF NUMBER OF INGREDIENTS USED TO PRODUCE A 160 g/kg DM COMPOUND FEED ON THE PROPORTION OF MIXES FALLING OUTSIDE DEFINED RANGES OF THE EXPECTED VALUE. (THESE FIGURES ASSUME THAT ALL INGREDIENTS SHOW THE SAME DEGREE OF BETWEEN BATCH VARIATION IN PROTEIN CONTENT AS THAT SHOWN FOR BARLEY AND SOYA IN *TABLE 3.3*)

Number of ingredients	*% of mixes falling outside of*	
	±10% expected value	*−10% to +20% expected value*
2	15	8
3	9	4
4	4	2

ingredients are subject to similar levels of between-batch variation, but this improvement has to be balanced against the increased errors associated with mixing, which are likely to increase as the number of ingredients increases. Such risks of producing compounds which fall outside the legal permitted range when formulations are based on standard tables of nutritional data may therefore justify analysis of each batch of ingredients.

Additional errors are involved when chemical analysis is used as an indirect measurement of a nutrient. The values obtained will be subject not only to the errors of the chemical determination used as a predictor, but also all of the errors accumulated in the derivation of the prediction equation. Regression equations such as those used to predict ME can only be approximate since they are calculated from sample values which are themselves affected by errors, although the residual standard deviation of the regression gives some measure of the size of these. In addition, the model upon which they are based is probably an oversimplification of the underlying causal biological factors.

Another source of error which is often overlooked is the use of a regression equation to predict values outside the range of the samples used to calculate it, that is by extrapolation. There are sound statistical reasons

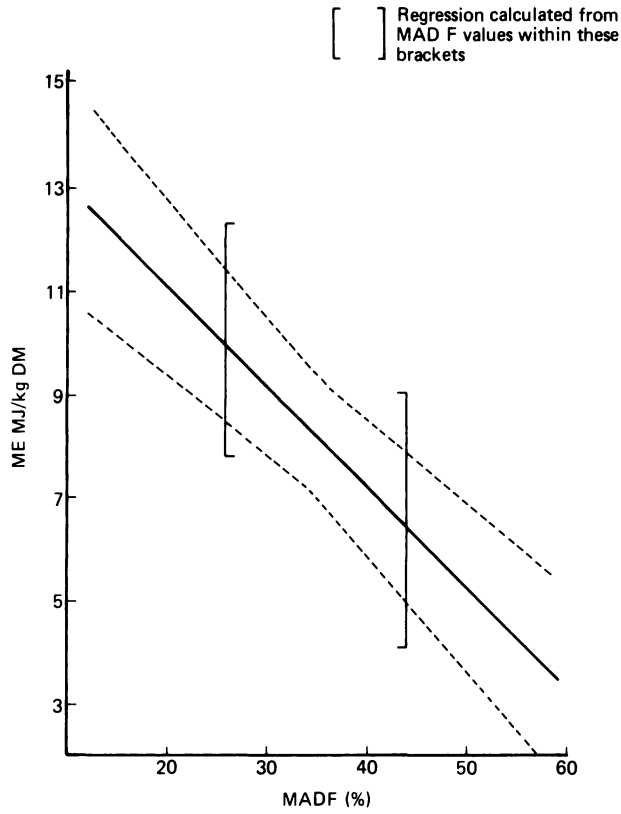


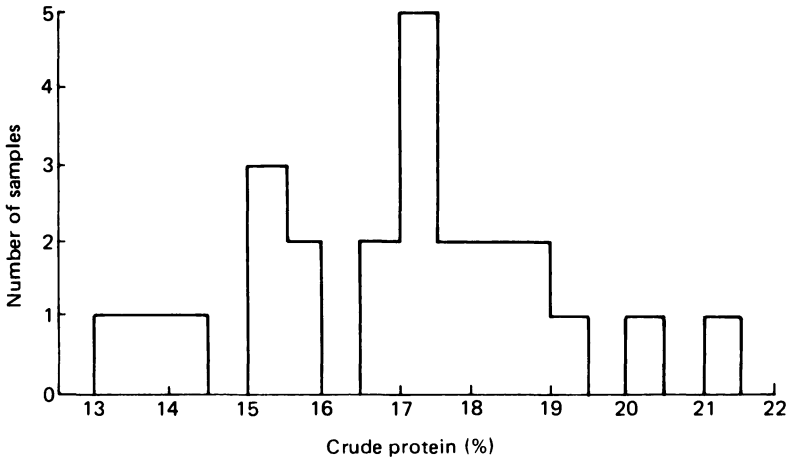
Figure 3.1 The regression of ME on MAD fibre showing the limits within which 95% of the points would be expected to lie

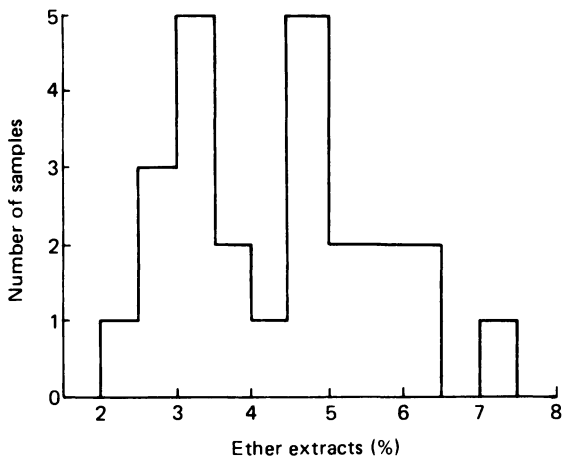
for avoiding this procedure, since the precision with which a value can be predicted decreases rapidly as the values of the predictor move away from the mean, even if the prediction equation is of a biologically reasonable form. This is shown by the 95% confidence intervals in *Figure 3.1* for the regression of ME on MAD Fibre for hay. In practice, the prediction equation is only a first approximation to the true function and considerable additional systematic error may occur if the equation is extrapolated.

For a prediction equation to be of value therefore two conditions must be fulfilled:

(1) The equation must be based on a broad but relevant spectrum of samples to give a wide range of values for the predictor.
(2) The chemical determination used for the predictor must give repeatable and reproducible results acceptable to both the nutritionist and analyst, i.e. variation both in results between repeated determinations within a laboratory, and between sub-samples sent to different laboratories must be acceptably small.

Condition 1 was fully appreciated by those who designed the recent trial on methods of predicting energy values of compound feeds, carried out by





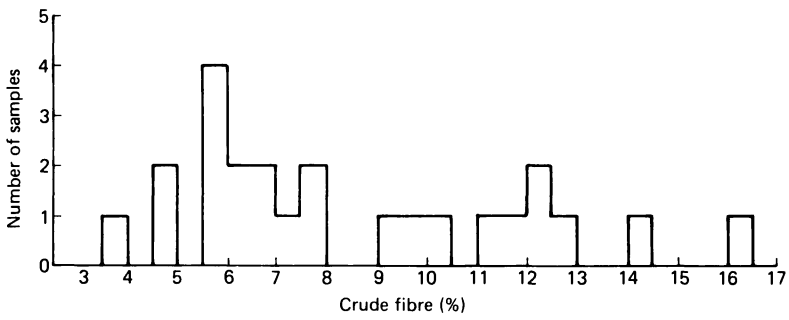


Figure 3.2 The distribution of the compounds used by the Rowett Research Institute relative to their proximate constituents

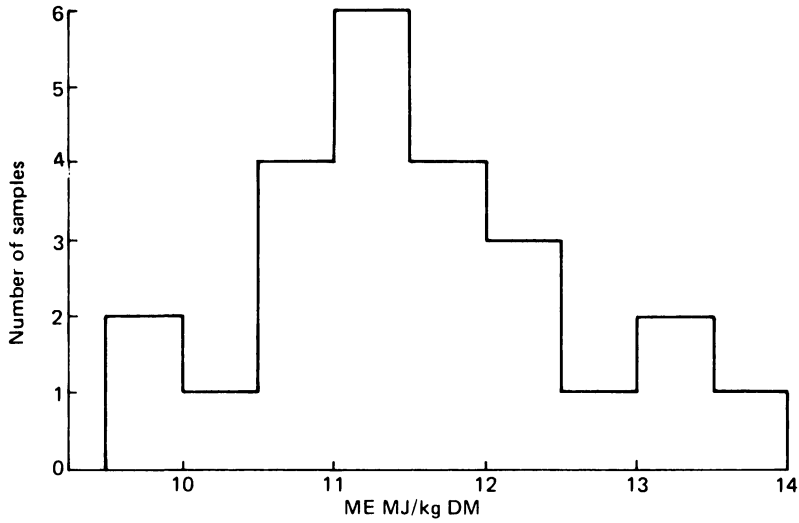


Figure 3.3 The distribution of the determined ME values of the 24 compounds used by the Rowett Research Institute (after Wainman, Dewey and Boyne, 1981)

the Rowett Research Institute (Wainman, Dewey and Boyne, 1981). The 24 compounds used were separately formulated to cover a wide range of ME values and ingredients, by varying the content of components such as CP, EE and CF. The resulting ranges of these components, and the determined ME values can be seen in *Figures 3.2* and *3.3*.

It is more difficult to meet condition 2. The implications of this condition are best illustrated by the results of a recently conducted 'ring test' in which 23 laboratories, spread throughout Europe, took part (MAFF, 1981). Samples of 11 feedstuffs of differing nature, ranging from straw to compound feedingstuffs, were prepared centrally, to minimize sampling and preparation error. Sub-samples were taken by quartering, and circulated to the participating laboratories, together with recommended methods of analysis. The methods were not mandatory, local variations being allowed. The objective was to determine the precision of each method, precision being defined as 'a composite quantity, depending upon

(1) variation in results arising from conditions specific to individual laboratories (between-laboratory variation),
(2) variation between replicates carried out in the same laboratory (within-laboratory variation),
(3) variation in results arising because laboratories deal with analytical problems associated with different samples in different ways (laboratory × sample interaction).'

The four determinations carried out were:

(1) neutral detergent fibre (NDF);
(2) neutral detergent fibre following pre-treatment with amylase (NDF-A);
(3) acid detergent fibre (ADF); and
(4) lignin (LIG).

Table 3.6 VARIATION IN ADF DETERMINATION WITHIN AND BETWEEN LABORATORIES FOR A COMMON SAMPLE OF SILAGE AND A COMPOUND FEED

Laboratory	*ADF (%)*			
	Silage		*Compound (low starch)*	
1	33.9	34.8	27.3	26.9
2	31.4	31.4	26.8	26.8
3	32.8	33.5	25.5	26.0
4	29.5	29.3	24.0	23.8
5	34.8	34.6	28.7	28.3
6	32.7	32.7	27.1	27.4
7	32.5	32.5	27.5	27.3
8	32.5	32.3	27.3	26.5
9	33.1	33.2	27.0	26.8
10	32.1	32.6	25.0	27.5
11	33.2	33.0	27.7	27.4
12	31.4	31.5	23.8	24.0
13	32.9	33.3	26.8	27.0
14	32.4	32.6	27.4	27.7
15	31.7	31.4	26.5	26.8
16	32.7	32.5	25.1	24.8
17	33.3	32.6	28.1	27.8
18	32.7	32.8	27.5	27.5
19	32.0	31.9	26.1	26.0
20	33.5	33.5	27.3	26.8
21	32.3	32.1	26.2	25.3
22	31.8	31.6	26.5	26.3
23	32.7	32.3	28.1	27.1

Source of variation	*Components of variance*	
	Silage	Compound
Between laboratories	1.035	1.254
Between replicates within laboratories	0.074	0.224

(From MAFF, 1981)

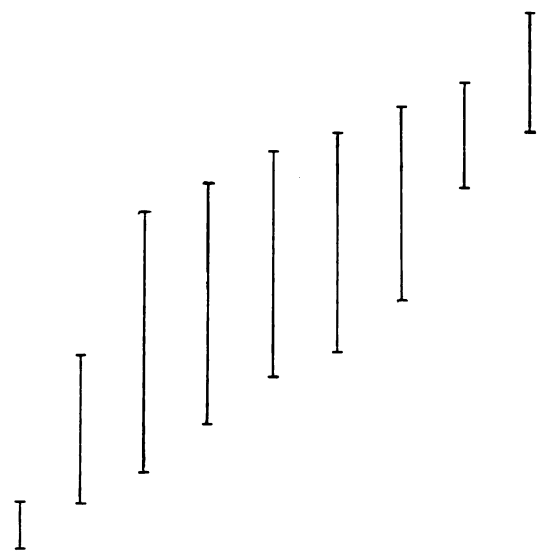
The data shown in *Table 3.6* are the ADF values obtained in this 'ring test' for one wilted grass silage and one low starch compound. The components of variance between laboratories and between replicates within laboratories are also shown. The latter component is used to measure repeatability, while both are used to measure reproducibility. The results for other feeds and determinations all show a similar degree of variation, with the between-laboratory component at least five times larger than the within-laboratory component.

From these values the absolute difference between two replicate determinations of ADF would be expected to be less than 0.796 for the silage and 1.386 for the compound 95% of the time. This level of repeatability may well be considered acceptable. Similarly, if the same sample were analysed in two different laboratories, the absolute difference between them would be expected to be less than 3.046 for the silage and 3.559 for the compound, which is far less acceptable.

The means of the duplicate results from all the laboratories have been tabulated in ascending order (*Tables 3.7* and *3.8*) and the results of Duncan's multiple range test marked by lines alongside. Results not

Table 3.7 DUNCAN'S MULTIPLE RANGE TEST USED TO COMPARE THE MEAN ADF VALUES FROM EACH OF 23 LABORATORIES: SILAGE

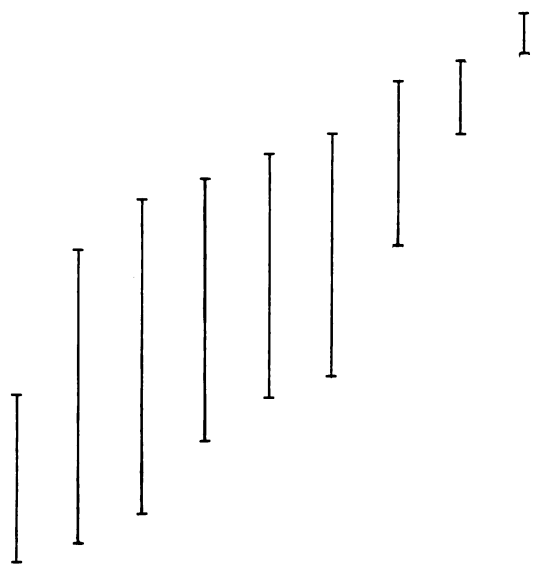
Laboratory	*Mean ADF %*
4	29.40
2	31.40
12	31.45
15	31.55
22	31.70
19	31.95
21	32.20
10	32.35
8	32.40
7	32.50
14	32.50
23	32.50
16	32.60
6	32.70
18	32.75
17	32.95
11	33.10
13	33.10
3	33.15
9	33.15
20	33.50
1	34.35
5	34.70



Results not sharing a common side line differ at least at the 5% level of significance (From MAFF, 1981)

Table 3.8 DUNCAN'S MULTIPLE RANGE TEST USED TO COMPARE THE MEAN ADF VALUES FROM EACH OF 23 LABORATORIES: COMPOUND

Laboratory	*Mean ADF %*
4	23.90
12	23.90
16	24.95
3	25.75
21	25.75
19	26.05
10	26.25
22	26.40
15	26.65
2	26.80
13	26.90
9	26.90
8	26.90
20	27.05
1	27.10
6	27.25
7	27.40
18	27.50
14	27.55
11	27.55
23	27.60
17	27.95
5	28.50



Results not sharing a common side line differ at least at the 5% level of significance (From MAFF, 1981)

Table 3.9 ANALYSIS-OF-VARIANCE TABLES OF THE ADF VALUES DETERMINED AT 12 LABORATORIES ON FOUR SAMPLES OF FEED

Source of variation	*df*	*SS*	*MS*	*VR*
Between samples	3	2509.40	836.467	—
Between laboratories	11	10.48	0.989	1.52
Lab. × sample interaction	33	21.44	0.650	12.03[a]
Between replicates	48	2.57	0.054	
Total	95	2544.29		

[a]Significant at 0.1% level

Table 3.10 MAD FIBRE DETERMINATION OF 28 SILAGES FROM FOUR DIFFERENT LABORATORIES

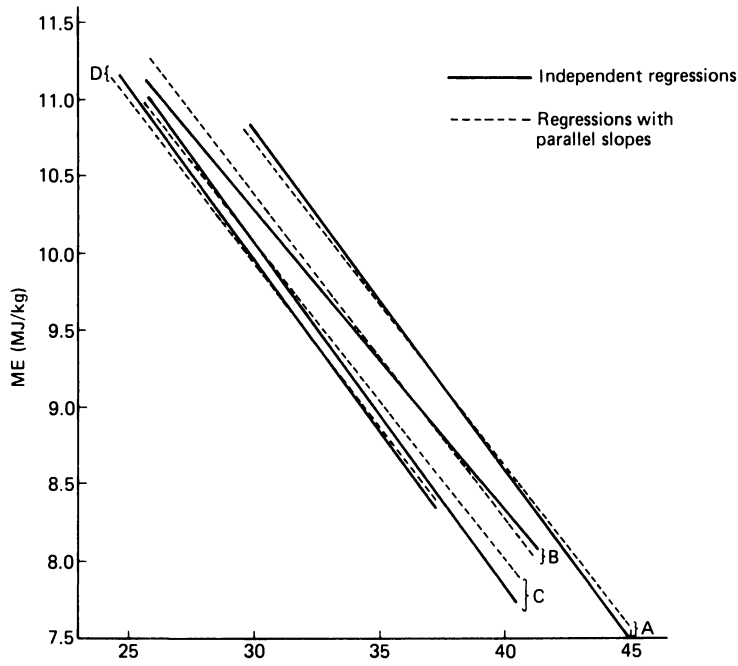
In vivo ME	*MAD Fibre (%)*			
	Laboratory			
	A	*B*	*C*	*D*
7.45	41.2	40.4	38.9	37.7
7.89	41.4	39.0	40.8	36.9
8.04	36.9	34.4	37.6	35.1
8.20	40.0	36.5	37.1	38.2
8.30	44.9	39.0	36.8	36.2
8.54	38.0	39.8	37.4	34.7
8.60	39.8	38.3	34.3	32.6
8.70	38.7	38.4	37.6	35.4
8.90	34.9	36.5	34.2	37.1
8.95	39.1	39.0	37.5	32.8
9.03	37.2	36.9	32.0	32.0
9.11	36.1	39.8	35.5	36.4
9.20	38.0	37.3	35.2	35.5
9.22	33.4	36.1	32.9	31.6
9.30	37.1	34.6	35.3	36.2
9.31	37.7	37.5	33.2	32.0
9.41	36.0	32.9	32.0	32.4
9.48	34.0	35.5	34.0	36.5
9.61	39.1	36.0	35.5	33.2
9.70	36.9	30.5	32.7	29.2
9.80	36.5	33.2	32.1	31.5
9.91	32.7	29.6	28.2	27.9
10.02	37.2	31.7	29.4	28.9
10.13	36.4	35.1	31.7	32.5
10.38	32.2	30.5	27.0	28.5
10.57	35.0	32.8	27.4	29.2
10.85	32.4	26.1	28.9	28.9
11.23	30.3	28.5	26.9	25.9

sharing a common side line are significantly different from each other at the 5% level.

From the ring test, data for four feeds were combined using the values produced by 12 laboratories, giving the analysis-of-variance shown in *Table 3.9*. There is a significant laboratory × sample (replicate) interaction indicating that the differences between laboratories are not consistent for different feeds. If the results for one feed are plotted against another the laboratories that give inconsistent results can be easily identified.

Thus a regression of ME (determined *in vivo*) against ADF would be much more precise if determined from analyses conducted in the same

laboratory as that used to analyse the sample for which ME predictors are needed than if it based on values from different laboratories. To demonstrate this further, consider the data in *Table 3.10*. Four laboratories determined the MAD Fibre in 28 samples of silage whose ME had been pre-determined *in vivo*. The data from each separate laboratory were used to calculate a predictive equation for ME to give the fitted lines shown in *Figure 3.4*. Combining these results gave the analysis-of-variance shown in



Laboratory	Regression equation	% variation accounted for
A	ME = 17.39 − 0.220 MADF	57.7
B	ME = 16.13 − 0.195 MADF	64.1
C	ME = 16.53 − 0.216 MADF	80.5
D	ME = 16.52 − 0.219 MADF	66.4
	Regression equations with parallel slopes	
A	ME = 17.07)	
B	ME = 16.72)	
C	ME = 16.38) − 0.211 MADF	68.0
D	ME = 16.26)	

Figure 3.4 Independent regressions of ME on MAD fibre for four laboratories (A, B, C, D) and their data combined to give parallel slopes

Table 3.11. This indicates that, although the means for each laboratory are significantly different from each other ($P<0.001$), the lines have similar slopes. Thus a set of parallel regression lines can be fitted, which are also shown in *Figure 3.4*. The variation in ME accounted for by these parallel lines is 68%, comparable with the independent regressions. However, when a pooled line is fitted this percentage reduces to 57%. Thus the error

in the predictions using a pooled line would be greater, due to the use of values from different laboratories. This point was made by Morgan and Whittemore (1982) and by Wiseman and Cole (1983).

The main reason for this increase in the error is the differences between the *y*-intercept of the separate lines, indicating the presence of bias, that is, the values produced by each laboratory are systematically different from each other and from the population mean, assuming that the laboratories are a random sample of all relevant laboratories. When the variation is mainly due to this sort of bias, it is possible to reduce it by improving the analytical method; however, the first problem is to identify the bias.

Table 3.11 ANALYSIS-OF-VARIANCE TABLE COMPARING THE SEPARATE REGRESSION LINES OF ME ON MAD FIBRE FROM EACH OF FOUR LABORATORIES

Source of variation	*df*	*SS*	*MS*	*VR*
Regression	1	50.7781	50.7781	189.31
Between laboratories	3	9.4482	3.1494	11.74[a]
Between slopes	3	0.1530	0.0510	0.19
Residual	104	27.8963	0.2682	
Total	111	88.2756		

[a]Significant at the 0.1% level

When the results from one 'ring test' are analysed, the results from some laboratories may be appreciably different from the general results. However, this may be due to chance, and in a further test other laboratories may differ. One test cannot show a continuing bias. This can only be shown by a series of ring tests carried out on a regular basis. Then, if one laboratory obtains results which are consistently different from the rest, the analyst in charge can take action. Even if the differences are not statistically significant, a trend may be discernible, in which case, the analyst may consider remedial action, or alternatively the nutritionist using the results may make an allowance when interpreting them. The course adopted will depend on the magnitude of the bias, the effort needed to correct it, and the purpose of the analysis.

The ADAS system of analytical monitoring of carefully prepared samples of standard feeds gives an early indication of unacceptable bias, and enables the analytical chemists to take immediate corrective action. Each week one sample each of a hay, a compound and a fishmeal are chemically analysed by each of the 12 ADAS Analytical Chemistry Departments for constituents such as crude protein, fibre, ash and minerals. Since the samples are feedstuffs, the 'true value' for any analytical determination is not known but has to be estimated from the mean of the results after the statistical elimination of any 'outliers'. Separate control charts are kept by each laboratory for each determination so that they can monitor their own progress against the mean value. *Figure 3.5* is an example of one of these charts, but includes the results from two laboratories. If there is no bias, the results from any one laboratory will be distributed at random around the mean line as with laboratory A in *Figure 3.5*. However, the results for laboratory B appear to be randomly distributed around a line somewhat removed from the mean thus indicating a bias.

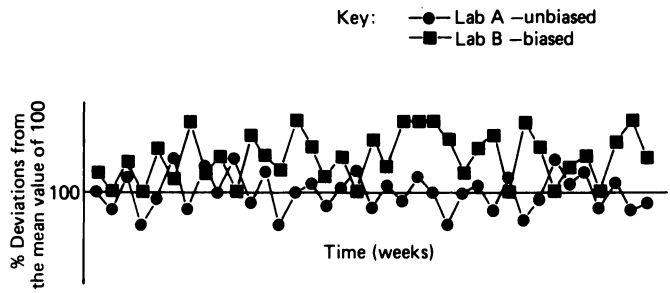


Figure 3.5 Control chart for two laboratories over a period of weeks. Note: Each week the mean value is adjusted to 100 then each laboratory plots:

$$\frac{\text{Lab. result} \times 100}{\text{Actual mean value}}$$

The bias is not always so obvious, and as the monitoring scheme depends on graphical methods for identifying bias, improved techniques are being considered. One of these is the CUSUM chart where each point is expressed as the deviation from the mean value (as with the current chart), but then added to the total of all the previous deviations before plotting. *Figure 3.6* shows an example of what happens when data are plotted on an ordinary control chart and on a CUSUM chart; the latter makes the bias much more obvious. This improvement will help to bring the Analytical Monitoring Scheme more in line with schemes used by clinical chemists, where large errors in analytical technique could be a matter of life or death to a hospital patient.

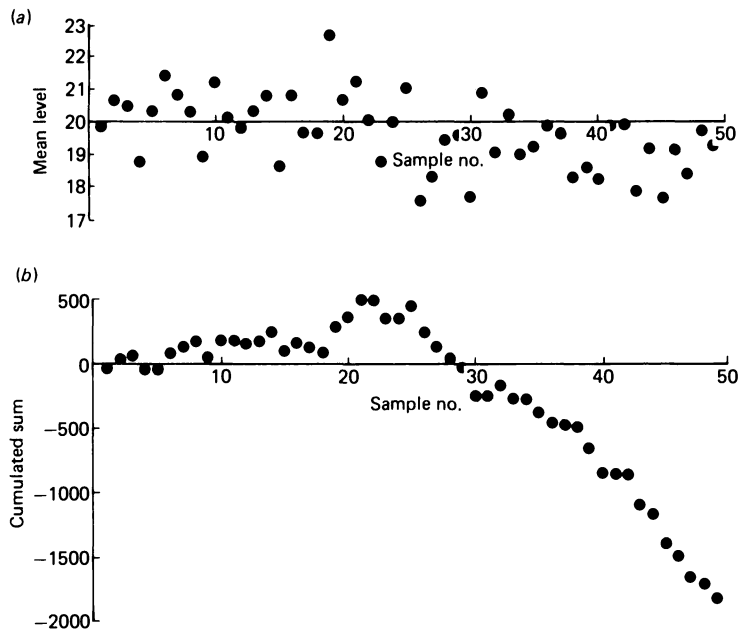


Figure 3.6 Example of how CUSUM charts improve the detection of bias. (a) Control chart of 50 consecutive mean values. (b) CUSUM chart of the same data

In practice the control chart used by ADAS analytical chemists (*Figure 3.5*) usually shows the 95% confidence limits. If an analyst finds that the results from his laboratory lie outside the limits on one occasion, he need not take action, because this is likely to occur between two and three times a year at random. However, three consecutive results outside the confidence limits, in the same direction, would call for immediate action. A small bias would take longer to identify, although the CUSUM chart would give an earlier warning than the control charts.

Once bias has been identified at a particular laboratory, the analyst in charge should make a thorough investigation of the method of chemical analysis as applied in his laboratory, in order to identify the cause of the bias and then to take the appropriate corrective action. If correcting an identified bias would either disrupt the laboratory system, or prove very expensive, the analyst should discuss the problem with the nutritionist, as it is possible for the latter to make allowances when using biased figures. This might be an acceptable compromise for advisory work, but not for a legal declaration.

Although this scheme has been described as 'the ADAS scheme' and is run weekly in ADAS laboratories, it should be noted that, for four weeks each year, the scope is enlarged to include laboratories from UKASTA and the Scottish Colleges. The results obtained are very encouraging. The MAD Fibre determination gives a narrow spread of values, thus justifying the use of one equation for the prediction of ME from MAD Fibre by the three advisory groups (ADAS, Scottish Colleges, UKASTA). A similar situation exists for the methods of the Weende system of proximate analysis, except for a small systematic discrepancy (now the subject of investigation) in the determination of crude protein between the laboratories of ADAS and UKASTA.

Morgan and Whittemore (1982) and Wiseman and Cole (1983) have both stated that the use of regression equations may be justified if all the chemical analysis is carried out in one laboratory, implying that the magnitude of between laboratory and laboratory × sample errors are so great as to render the predicted values useless. However, this is not so when close agreement can be reached between properly organized laboratories.

In conclusion, it must be remembered that the nutritionist and the analyst are involved with the planning of diets, which are fed to animals with varying degree of accuracy. There is little that advisers can do about this source of variation, except to recognize its existence and to make recommendations, to the farmer, on its reduction. However, the existence of on-farm error, however large, must not be used as an excuse for sloppy work by the analyst or by the nutritionist.

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4

CEREAL REPLACERS AS ALTERNATIVE SOURCES OF ENERGY FOR PIGS

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Cereal replacers in Northern Ireland

Animal feed manufacturers in Northern Ireland have made more use of cereal replacers than their counterparts in the rest of the UK. There are two possible reasons for this. First because Northern Ireland is, to a marked extent, a cereal-deficient area, cereals are usually more expensive here than in the rest of the UK. A second reason is the competition afforded by on-farm mixers who may make use of cheaper farm-grown or imported barley. For these reasons the compounders in Northern Ireland are thought to include substantial proportions of cereal replacers, particularly cassava, in their pig finishing and possibly also in their sow diets.

Table 4.1 QUANTITIES OF CASSAVA IMPORTED INTO DIFFERENT AREAS

Area	*1976*	*1977*	*1978*	*1979*	*1980*	*1981*	*1982*[a]
				('000 tonnes/year)			
EEC	2984	3801	5976	5376	4866	6594	(6500)
UK[b]	7	7	14	29	28	402	(945)
Northern Ireland	—	—	0.6	10	17	80	(170)

Sources: Department of Agriculture for Northern Ireland (unpublished data); Home Grown Cereals Authority (1981, 1982a, 1982b)
[a]Projected values
[b]Includes Northern Ireland

The total annual quantity of cassava imported into the EEC has been more or less static for the past few years but the quantities entering the UK and especially Northern Ireland have increased substantially in the last two years (*Table 4.1*). In 1981/82 Northern Ireland received some 17% of the cassava imported into the UK although it produced only about 10% of the total compound feed.

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Table 4.2 THE ANNUAL PRODUCTION OF COMPOUND FEEDING STUFFS FOR PIGS IN NORTHERN IRELAND

	1978/79	*1979/80*	*1980/81*	*1981/82*
		('000 tonnes)		
Production by compounders	369	333	259	230
Estimated total consumption[a]	427	422	395	356
Estimated proportion produced by compounders	0.86	0.79	0.66	0.65

Sources: Home Grown Cereals Authority (1982c); Department of Agriculture for Northern Ireland (1982)
[a]5.5 × no. of sows at beginning of accounting year

This high use of cassava and of other cereal substitutes has been essential for the Northern Ireland compound trade to remain competitive with farm mixing. Data collected by the Department of Agriculture for Northern Ireland (1982) and the Home Grown Cereals Authority (1982c), however, suggest that in recent years a substantial proportion of pig producers have changed to farm mixing (*Table 4.2*), a trend which may reflect some resistance by pig farmers to the inclusion of high levels of cassava in pig feeds. The practice by some compound manufacturers of presenting the same diet formulated with or without cassava is further evidence of this resistance on the part of Northern Ireland's pig feeders.

Cassava

The use of cassava in feeds for pigs and other species has been reviewed by Pond and Maner (1974), Muller, Chou and Nah (1975) and Oke (1978). This material is known by a variety of names including cassava, tapioca and manioc, the latter arising from the generic name of the parent plant *Manihot* from which the root is harvested. The product is also described with regard to the processing of the root (Muller, Chou and Nah, 1975). The simplest processing involves slicing or chopping and drying the resultant particles or chips in the sun. The dried chips may be ground to a fine powder, the so-called 'native' form, or may, in turn, be pelleted prior to export. Pelleted cassava is the commonest form in use in western Europe. The pellets may be damaged in transit and the 'fines' containing a varying proportion of pellets may be traded under the name 'native'.

CYANIDE IN CASSAVA

Peel forms about 14% of the mature harvested root (Pond and Maner, 1974; Cooke and De la Cruz, 1982) and contains from less than one to more than 15 times as much cyanogenic glucoside as does the pulp (Sinha and Nair, 1968). Linamarin is the major glucoside and, following damage to the plant tissue, it is hydrolysed by the endogenous enzyme linamarase to free hydrogen cyanide (HCN). The glucoside is referred to as bound HCN and analysis should account for both the bound and free forms. HCN contents as high as 1000 mg/kg (Sinha and Nair, 1968) and 600 mg/kg

(Cooke and De la Cruz, 1982) have been reported in root peelings and in the peeled root respectively prior to processing. Considerable variation exists depending on variety, soil type, climate and fertilizer application (Oke, 1965). The HCN content is a cause for concern when cassava forms a large part of the diet particularly in human populations. Much has been written on the role of cassava in the symptoms of goitre, cretinism and mental retardation (Dorozynski, 1978; Ermans *et al.*, 1980). For human consumption the root cortex which contains the majority of the cyanogenic glucoside is removed by peeling but this is not the case for animal feed. It is reported that traditional processing, that is slicing and sun drying, is unlikely to remove all the bound and free cyanide (Cooke and Madnagwa, 1978).

Oke (1978), in his review, suggested that cyanide content varied from 75 to 350 mg/kg. Presumably he was considering processed material although he did not explicitly state the origin of these values. Recent imports of cassava into Europe appear to have lower cyanide contents (*Table 4.3*).

Table 4.3 HCN CONTENT (mg/kg) OF SAMPLES OF CASSAVA IMPORTED INTO THE EEC

Country of origin	*Form of cassava*	*Reference*					
		(1)	*(2)*	*(3)*	*(4a)*	*(4b)*	*(4c)*
Thailand	Pellets	41	5–7	3	12	9	5
Thailand	'Native'		3	3			
Malawi	'Native'	58					
India	Chips		16				
Indonesia	Chips		27				

Reference and analytical methods
(1) Perez *et al.* (1981) method not stated
(2) Mathers, J., personal communication. AOAC (1975)
(3) Stephenson, Hilary, personal communication. AOAC (1980) acid titration.
(4) Porter, M., personal communication (a) Sinha and Nair (1968) modified; (b) HMSO (1976); (c) AOAC (1980) acid titration

The precision of the determination of bound-plus-free HCN has been questioned by Cooke (1978) who suggested an alternative enzymatic method developed with fresh cassava tissue.

The regulations governing the composition of feedstuffs (HMSO, 1976) allow maximum levels of HCN in imported cassava of 100 mg/kg and in complete compound feeds for pigs of 50 mg/kg. There is to be no change in these values in the revised regulations which came into force in February 1983. The level of free-plus-bound HCN in diets containing cassava is crucial to the performance of pigs, especially young pigs (Khajarern *et al.*, 1977; Hew, 1977). After ingestion the glucoside is hydrolysed to HCN, small amounts of which can be detoxified to thiocyanide and excreted in the urine. The detoxification is dependent on sulphur, the principal source of which is likely to be methionine, although elemental sulphur may be provided as an alternative source (Job, 1975).

OTHER FACTORS AFFECTING THE USE OF CASSAVA

The potential level of HCN in complete diets is one factor influencing the maximum inclusion of cassava in pig diets. Other factors have been

Table 4.4 ANALYSES (%) OF BATCHES OF CASSAVA (1981–82)

Source of data	*Moisture*			*Crude protein*			*Crude fibre*			*Oil*			*Ash*			*Insoluble ash*			*Starch*		
	$\bar{\chi}$	*SD*	*n*	$\bar{\chi}$	*SD*	*n*	$\bar{\chi}$	*SD*	*n*	$\bar{\chi}$	*SD*	*n*	$\bar{\chi}$	*SD*	*n*	$\bar{\chi}$	*SD*	*n*	$\bar{\chi}$	*SD*	*n*
Agricultural Research Institute of NI, Hillsborough	11.0	0.58	16	2.5	0.27	13	3.4	0.40	13	0.7	0.19	12	5.7	0.66	15	3.9	—	2	67.2[a]	2.2	9
Isaac Andrews & Sons Ltd	11.6	1.00	30	2.5	0.29	32	—	—	—	—	—	—	4.7	0.59	30	—	—	—	—	—	—
J. Bibby (Agric.) Ltd, GB data	11.5	1.26	25	2.6	0.53	15	3.2	0.69	43	0.6	0.34	16	5.1	0.75	44	2.7	0.54	32	70.9	2.5	42
NI data	10.8	0.70	27	2.5	0.23	27	—	—	—	0.7	0.17	27	5.2	0.73	27	—	—	—	—	—	—
E.T. Green Ltd	11.4	0.78	5	3.4	0.55	79	3.4	0.67	12	0.6	0.27	75	4.6	0.46	26	2.3	0.35	8	70.0	1.3	8
BOCM Silcock (NI) Ltd[b]	13.3	0.73	42	2.7	0.33	42	3.0	0.64	11	0.4	0.12	42	4.7	1.00	42	—	—	—	—	—	—
John Thompson & Sons Ltd	11.0	Range (9.6–12.4)		2.6	Range (1.9–3.6)		3.6	Range (3.3–4.2)		0.6	Range (0.3–1.1)		5.5	Range (4.6–5.9)		2	Range (—)		—	Range (68–71)	

[a]Enzymatic method
[b]'Native' cassava

reviewed by Oke (1978) and Jordan (1982) and include the variation in composition from batch to batch, the palatability and enteric effects of diets containing cassava. Major considerations on the farm are the dustiness of the material and the abrasiveness of the insoluble ash fraction and its tendency to separate in wet feeding systems. Other considerations, probably of minor importance in pig diets, include the availability of its lysine, its essential fatty acid content, its mineral imbalance, its ulcerogenic effect and its mycotoxin content.

The variability in composition of cassava is indicated in *Table 4.4*. These data do not support the commonly expressed view of the high degree of variability exhibited by cassava.

The palatability of cassava is of importance particularly when pigs are fed *ad libitum*. The depression in growth rate reported by Muller, Chou and Nah (1975) in finishing pigs fed *ad libitum* on diets containing in excess of 30% cassava may be partly due to the lower palatability of these diets. Further evidence that finishing pigs fed *ad libitum* will consume less when the diet contains 50% or more cassava is presented by Portela and Maner (1972) and by Maner, Baitrago and Jiminez (1967). The dustiness of unpelleted diets may reduce palatability but when dust is eliminated by forming a wet mash pigs may still be reluctant to eat (Henry, 1970). Our own observations show that when pigs are penned singly, some individuals may require as long as 4 h to consume half their daily ration when fed a diet containing 0.72 cassava as a wet mash. These pigs, which weighed between 30 and 35 kg, had been abruptly transferred from a barley/soya/fishmeal diet and fed at a rate of about three times their maintenance requirement. The rate of consumption increased and as the pigs became accustomed to the new diet after one or two weeks, was normal for nearly all pigs. No such problems were observed with identical feeding and management when pigs were fed in groups.

Diarrhoea has been reported as a problem with young pigs fed diets containing 20–40% cassava (O'Grady and Hanrahan, 1979) or fed a 'high' level (Anon., 1982). In contrast Aumaitre (1969) found the incidence of diarrhoea was reduced when cassava was included in the diet of pigs weaned at five weeks of age. The type of starch affects the site of digestibility in the intestine (Rerat, 1981) and the high proportion of amylopectin (70%) in cassava starch (Oke, 1978) increases the undigested portion of carbohydrate in the ileo-rectum of the monogastric increasing the substrate for microbial activity. The observations of Maner, Baitrago and Jiminez (1967) suggest that the cyanide content of cassava may be a further contributing factor to the onset of diarrhoea. In general, diarrhoea has not been a problem in the experiments carried out at the Agricultural Research Institute, Hillsborough except on one occasion (Walker, 1982) and that was of a minor nature. It is sometimes suggested that constipation rather than looseness of the faeces is the more likely problem with sows fed diets containing high proportions of cassava, due to the low fibre content of such diets. Our own experience is that sow diets containing 50% cassava produces faeces of similar consistency to those from a barley/soya diet.

In the past it has been recommended that cassava in finishing pig diets should not exceed 40% (Muller, Chou and Nah, 1975). In experiments using least-cost diets, Walker and Kilpatrick (1980) constrained cassava

contents of the diet to 30% but found that pig performance was less than that expected, due, it is thought in retrospect, to overvaluation of the nutritive value of the cassava. It was predicted by Robb (1976) that as cassava was detoxified, the levels of inclusion would be raised. Since then there have been reports of the use of finishing pig diets containing 70% cassava with no resultant reduction in performance (Muller, Chou and Nah, 1972; Job, 1975). The price of cassava in Northern ireland does not restrict the quantity included in finishing pig diets. Assuming there is ample screening to give warning of consignments with high HCN contents, there appear to be few nutritional reasons for applying constraints in the formulations for finishing pigs.

CASSAVA EXPERIMENTS AT HILLSBOROUGH

In the experiments at Hillsborough, diets were fed wet, with no rigorous control on the meal:water ratio. This was estimated to range from 1:1.5 to 1:2. All pigs were fed twice a day and feed was rationed according to the scale in *Table 4.5*. The method was to formulate the diets without any

Table 4.5 FEEDING SCALE USED IN CASSAVA EXPERIMENTS AT HILLSBOROUGH

	Week no.								
	1	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*
Initial live weight[a] (kg)	27	30	33						
MJ DE/pig/day	17.8	19.1	20.3	21.6	23.5	25.4	28.0	29.9	31.8

[a]If the initial live weight was, for example, 30 kg the daily allowance was 19.1 MJ DE in the first week, 20.3 MJ DE in the second week, etc.

constraint on energy density while holding constant the ratio of other nutrients to energy. The weight of feed allowed per day was adjusted to give iso-nutrient intakes. The diets were introduced abruptly and the ration was reduced for a few days to overcome any problems of acceptability.

The first two experiments were concerned with the level of inclusion of cassava. The first experiment involved 360 pigs and was a factorial design with cassava included at 0, 150, 300 or 450 kg/tonne and tallow at 0, 50 or 100 kg/tonne. As this experiment progressed it was clear that the highest level of cassava was not resulting in any major reduction in performance and the second experiment was therefore run concurrently. This was a randomized block design with four levels of cassava; 0, 238, 475 or 713 kg/tonne, and so far it has involved 280 pigs. The digestible energy values for the major ingredients at all rates of inclusion were assumed to be cassava, 14.2; barley, 12.7; tallow, 32.1 and dehulled soya bean, 14.5 MJ/kg as fed. Examples of the diets in these experiments are shown in *Table 4.6*.

The results of the extreme treatments of cassava experiments 1 and 2 are presented in *Table 4.7*. They show that growth rate declined with increasing cassava levels but that feed conversion ratio and killing out percentage were hardly affected. This suggests that the nutrient densities of the diets containing cassava had been overestimated thereby invalidating the

Table 4.6 EXAMPLES OF DIETS USED IN THE CASSAVA EXPERIMENTS AT HILLSBOROUGH

	Experiment no.				
	1	*1*	*1*	*1 and 2*	*2 and 3*
Cassava	450	0	450	0	713
Barley meal	135	645	299	807	0
Tallow	100	100	0	0	0
Dehulled soya bean	282	226	224	170	258
Methionine	1.3	0.4	0.9	0	1.4
Dicalcium phosphate	20	12	14	6	20
Limestone	4	10	6	11	1.5
NaCl	3.7	3.5	3.2	3.0	3.3
Trace mineral/vitamin	3.6	3.5	3.3	3.0	3.3
Analysis (per kg as fed)					
calculated DE[a] (MJ)	15.4	14.7	13.3	12.7	13.9
dry matter (g)	900	900	883	884	892
nitrogen × 6.25 (g)	148	158	146	164	153
crude fibre (g)	34	46	41	49	31
ash (g)	72	55	68	47	80
oil (g)	109	113	13	19	10

[a]Assuming a value for cassava of 14.2. The subsequent experimental results suggested a lower value.

Table 4.7 THE EFFECT OF CASSAVA ON THE PERFORMANCE OF PIGS FROM 35 TO 85 kg LIVE WEIGHT[a]

	Cassava content in diet (kg/tonne)					
	Experiment 1			*Experiment 2*		
	0	*450*	*SE mean*	*0*	*715*	*SE mean*
Growth rate (g/kg)	710	688	8	741	680	10
Feed conversion ratio	2.80	2.78	0.05	2.99	3.01	0.05
Kill out (%)	78.1	77.9	0.2	76.2	76.8	0.2
Backfat thickness at P_2 (mm)	14.8	15.6	0.3	15.2	15.9	0.3
Carcase length (cm)	79.8	78.8	0.3	79.2	78.4	0.2

[a]Only the results of the extreme treatments are presented here. No differences were significant except growth rate in experiment 2 ($P<0.01$)

assumption of iso-nutrient intakes on all treatments. The result of this error was that pigs assigned to the cassava-containing diets had been underfed, which presumably resulted in the lower growth rates. The effects on carcase fatness and length, although statistical non-significance, were consistent in both experiments, and indicate possible nutrient imbalances in the cassava-containing diets.

DIGESTIBLE ENERGY OF CASSAVA

When these experiments were planned it was assumed on the basis of literature reports (Anon., 1977; Aumaitre, 1969; Muller, Chou and Nah, 1975; Pond and Maner, 1974) that the digestible energy of cassava was 14.2 MJ/kg as fed (110 g/kg moisture). The results of the second cassava experiment were used to estimate the DE value of cassava. The values for barley and dehulled soya bean meal given above were used. It was assumed

that growth rate was directly proportional to DE consumption. This assumption allowed the estimation of the amount of DE consumed per day for the cassava-containing diets. These values were adjusted for differences in the rates of fat production between treatments assuming

(1) that an increase of 1 mm backfat thickness at P_2 is equivalent to an increase of 1.2 percentiles in fat content in the carcase (Whittemore and Elsley, 1977)
(2) that the ratio of ME to DE is 0.96, and
(3) that it requires 53.5 MJ ME to deposit 1 kg fat (Agricultural Research Council, 1981).

The calculated DE values for cassava for the diets containing 238, 475 and 713 kg/tonnes cassava were 12.9, 12.4 and 12.7 MJ/kg air dry matter respectively. These are considerably lower than the published values given above but are closer to the figure reported by Perez *et al.* (1981) of 13.0 MJ/kg as fed for cassava from Thailand containing 65% starch. This would be similar to the type of cassava used in the Hillsborough experiments. Perez *et al.* (1981) also reported a DE value of 14.3 MJ/kg for cassava from Malawi containing 74% starch. Recently the digestible energy of a batch of cassava used in the Hillsborough growth experiments was measured as 14.0 MJ/kg air-dry material (K.J. McCracken, personal communication) but it was found that the utilization of ME was lower than that from control diets. This lower utilization would be accounted for in the modified 'DE' value calculated from the Hillsborough results. It would thus appear that the DE value of cassava calculated by a digestibility trial should be discounted when used in diet formulation by linear programming.

METHIONINE SUPPLEMENTATION OF CASSAVA DIETS

In view of the low HCN levels found in shipments of cassava from Thailand in the past few years it may not be necessary to supply a surplus of methionine for detoxification. This is currently under consideration at Hillsborough in a third experiment. The diet used in experiment 2 containing 713 kg cassava and 1.4 kg synthetic methionine per tonne (*Table 4.6*) is under comparison with similar diets supplemented with 0.7 or 0 kg synthetic methionine. The calculated total methionine + cystine contents of the three diets are 5.4, 4.7 and 4.0 g/kg air dry diet respectively and the proportions of these amino acids to lysine are 0.61, 0.53 and 0.45 respectively. The last of these diets with no synthetic methionine added may not be sufficient to provide the sulphur amino acid requirements of the finishing pig (Agricultural Research Council, 1981). Results from 42 individually-penned pigs (*Table 4.8*) suggest there is a small but a non-significant advantage in liveweight gain and feed conversion efficiency when synthetic methionine is added to a diet based on cassava and dehulled soya bean as the only major ingredients. The interim results from a group feeding experiment are confirming this trend and suggesting an even larger advantage in favour of the higher level of supplementary methionine.

Table 4.8 THE RESPONSE OF FINISHING PIGS TO SUPPLEMENTARY METHIONINE WHEN FED A DIET CONTAINING 713 kg CASSAVA/TONNE

	Sulphur amino acids (g/kg air dry diet)			*SE mean*	*Statistical significance*
Synthetic methionine	0	0.7	1.4		
Total methionine + cystine	4.0	4.7	5.4		
Growth rate (g/day)	701	719	721	14	NS
Feed conversion ratio	2.87	2.83	2.83	0.06	NS

The limited data on the response to supplementary methionine was reviewed by Adegbola (1977) who found one instance (Job, 1975) in which there was no response when a diet based on 71% cassava and 24.5% soya bean meal and containing 90 ppm cyanide was supplemented with either 2 g methionine/kg or alternative sulphur sources. Contrasting evidence was reported by Hew and Hutagalung (1972) and by Pond and Maner (1974) who found growth responses to methionine when added to diets containing about 50% cassava. In both cases the addition of fat (palm oil or beef tallow) to the basal diet was found to nullify the effects of methionine. More recently O'Grady and Hanrahan (1979) reported a positive but non-significant response when a cassava/soya diet containing 3.8 g methionine plus cystine/kg was supplemented with 1.8 g methionine.

As stated above the interaction between cassava and tallow was investigated in the first experiment. The results show a significant interaction between the two ingredients. The decline in growth rate with increasing levels of cassava was arrested when tallow was included in the diets (*Table 4.9*). With the system of feed rationing employed, growth rates would have

Table 4.9 THE INTERACTION[a] BETWEEN CASSAVA AND TALLOW ON GROWTH RATE (g/day) IN FINISHING PIGS

	Cassava in diet (kg/tonne)				
	0	*150*	*300*	*450*	
Tallow in diet (kg/tonne)	0	721	720	670	662
	50	723	690	697	698
	100	686	704	728	703

[a]The interaction is statistically significant ($P = 0.013$) and the standard error of a mean is 13.2

been equal on all treatments if the estimated DE values had been additive and if energy in the different ingredients had been utilized with equal efficiency.

It may be possible to improve further the performance of pigs fed diets containing cassava by attention to the mineral and vitamin components of the diet. The calcium and phosphorus contents of cassava root meals are often relatively high but other minerals notably copper, iron and zinc are relatively low (Hutagalung, 1977). The balance of these minerals together with iodine and cobalt should be considered. Hutagalung (1977) also draws attention to the vitamin levels in cassava meal, in particular to the content of β-carotene (vitamin A), D-α-tocopherol (vitamin E), nicotinic acid, biotin and cyanocobalamin (vitamin B_{12}).

CASSAVA FOR SOWS

Published results from feeding cassava to sows is limited. Gomez (1977) compared cassava meal/soya diets with maize/soya diets fed to gilts from 20 kg liveweight through rearing and their first parity. Significantly fewer pigs (three per litter) were reared by the cassava-fed gilts confirming the trends found previously by this author with fresh cassava and those reported by Pond and Maner (1974) for both fresh and dried cassava. Neither these experiments nor the one in progress at Hillsborough have more than 16 sows per treatment (10 to 16) although the latter will continue for three successive parities. The trend towards a smaller litter size on cassava diets found by the American workers appears to be supported by the interim results at Hillsborough when 25 or 50% cassava is included in sow diets. However these results contrast with those of Gomez (1979) who reported normal reproductive rates from sows fed cassava diets. There is also a possibility that culling rates are higher at Hillsborough on the cassava diets.

The financial advantage from including cassava in diets should be discounted for the cost of the extra wear on mills, conveyors and pelleting equipment caused by its silica content. This cost has not been defined. Further discounting may be necessary because of the loss which can occur during handling due to the dust produced from this material. On the farm the greater physical density of diets containing cassava must be taken into account when measuring feed allowances volumetrically. For example, the diets used in the second experiment (*Table 4.6*) have, in meal form, relative densities of 0.68 and 0.82 kg/ℓ for cassava contents of 0 and 713 kg/tonne respectively.

Molasses

With the agreement to control the future quantity of cassava imported into the EEC, its price advantage over cereals is likely to be reduced. A cereal replacer with a greater financial advantage at the present time is molasses. If it is unconstrained, it would be included at the rate of over 20% in a least-cost pig finishing diet. One product available to agricultural users in the UK is final molasses. Final molasses differs from high-test molasses, a product used for animal feeding in the tropics but imported into the UK for industrial use only, by having less total sugar and more ash, in particular a higher potassium content (Pond and Maner, 1974).

High-test molasses can be incorporated in finishing pig diets at levels in excess of 70% without detrimental effect (Velazquez and Preston, 1970) whereas high contents of final molasses have a laxative effect which may be intolerable. To prevent diarrhoea, maximum levels of 10, 20 or 30% final molasses were suggested by Iwanaga and Otagaki (1959) in the diets of pigs weighing 13–34, 35–68 and 69–90 kg respectively. Similar maxima have been suggested by other authors (Pond and Maner, 1974; Babatunde, Fetuga and Oyenuga, 1975; Osuji, 1982; Christon and Le Dividich, 1978) although it has been shown that the addition of crude or refined sugar to diets containing a high content of final molasses may be beneficial (Preston

and Willis, 1969 and 1970). Reasons for the laxative effect of final molasses have been discussed by Pond and Maner (1974) and by Christon and Le Dividich (1978) who conclude that this is probably an additive result from a number of factors. These include the increase in osmotic pressure caused by high levels of potassium and other minerals and the presence of sugars such as raffinose which are poorly hydrolysed by the pig. An inadequacy of intestinal sucrose seems an unlikely explanation since high levels of dietary sucrose can be efficiently utilized by the pig (Maner *et al.*, 1969). There are, however, adaptive processes which occur in response to dietary molasses and these probably include an increase in the specific activity of intestinal invertase, as found in the rat (Le Dividich *et al.*, 1978) resulting in an improvement in the utilization of molasses by the pig (Christon and Le Dividich, 1978). It would be beneficial therefore if a system of gradual introduction of molasses into the diet could be arranged in a commercial feeding system.

The digestible energy of final molasses has been reported as 10.0 MJ/kg by Christon and Le Dividich (1978) and by T.J. Hanrahan (personal communication) and as 10.3 MJ/kg by NRC (1979). However the apparent digestibility of the energy declines with increasing additions of molasses to the diet, particularly in the young pig (Le Dividich and Canope, 1975). Increasing content has a similarly depressing effect on nitrogen retention (Christon and Le Dividich, 1978). As with cassava, this reported DE value may require to be discounted possibly to between 6.5 and 9.5 as suggested by the growth trial results of Brooks (1972) and Hanrahan (1978). The possible reduction in killing-out percentage suggested by Christon and Le Dividich (1978) due to the inclusion of molasses in the diet should be included in any discounting calculations.

Molasses can be most easily utilized in a wet feeding system by mixing it directly with water and possibly also with milk by-products, as well as a balancing meal. Incorporation into the drinking system has, from limited observations (Walker, unpublished results) a number of drawbacks ranging from gorging and subsequent diarrhoea to refusal to consume the liquid and subsequent dehydration. The maximum inclusion of molasses in the mixing and pelleting of feeds is governed by the stickiness of the material. Acceptable pellets for pigs have been made by including 10% molasses in the diet, but the shelf-life of such a product is unknown and the reduction in nutrient density of such a formulation may not be acceptable to the majority of feed manufacturers.

Silage effluent

Silage effluent is more valuable than a mere cereal replacer, being ideally balanced for digestible energy and amino acids for the finishing pig (Patterson and Walker, 1979b), although it does contain an excess of minerals, potassium in particular (Patterson and Walker, 1979a). In regions where silage effluent is available, the saving in feed costs due to its use can be in excess of £3 per pig after allowing for the cost of its collection and storage. It has been estimated (Patterson, D.C., personal communication) that the capture and use of all the silage effluent produced in

Northern Ireland would replace in excess of 40000 tonnes of pig feed per annum, amounting to over 10% of the amount used in the Province (*Table 4.2*) and possibly as much as 40% of manufactured finishing pig feed. Although all silage effluent is unlikely to be diverted for this use, the large loss in efficiency which effluent represents (5% in the climatic conditions prevailing in Northern Ireland) is unlikely to be ignored in the future. Silage effluent has an advantage over molasses for pig feeding in that it can be fed either with meal in wet feed or with pelleted feeds by offering the effluent through the drinking system (Patterson, 1981). It is estimated that some 20000 pigs have now been fed silage effluent at rates equivalent to as high as 15% of their diet (Patterson and Walker, 1980).

Little is known about the additivity of the wet or semi-dry cereal replacers. If one accepts constraints for individual ingredients of 3.3 ℓ/day each for silage effluent and skim milk, 6.8 ℓ/day for whey and 20% of the total diet for molasses, and if there is no detrimental interaction between these ingredients, then the theoretical saving in feed costs compared with a barley plus soya bean meal diet of the type indicated in *Table 4.6* exceeds £4 per finishing pig. The inclusion of cassava may increase this saving further depending on the current price situation. So far as is known the additivity of this combination of ingredients has not been tested and the physical properties of such a mixture may well introduce some problems with the mechanical apparatus for the efficient dispensing of such a diet.

Comparison of control diet with manufactured compounds

Recently the barley/soya diet used for the control treatments for the finishing pig in experiments reported here (*Table 4.6*) was compared with two leading brands of manufactured feed and they were found to be not

Table 4.10 A COMPARISON OF A BARLEY/SOYA BEAN MEAL DIET WITH MANUFACTURED COMPOUNDS FOR FINISHING PIGS

	Barley/ soya	*Compound A*	*Compound B*	*SE mean*
No. of pigs	80	80	80	—
Calculated DE of diets (MJ/kg)	12.7	13.3	14.0	—
Growth rate (g/day)	778	787	782	6.5 NS
Feed conversion ratio	2.72	2.56	2.47	0.02[a]
Energy conversion ratio (MJ DE/kg carcase gain)	44.5	43.7	43.5	—
Backfat thickness at P_2 (mm)	15.6	16.2	16.7	0.3 NS

[a] $P<0.001$

significantly different when compared on the basis of conversion of digestible energy to carcase weight (Walker and Patterson, 1982). A summary of the principal results is given in *Table 4.10*.

Conclusions

In conclusion the most cost effective cereal replacers for finishing pigs are those with relatively low dry matter content which cannot be used by feed

manufacturers. Molasses, which is of intermediate dry matter content, can contribute to moderate financial savings at present if it can be incorporated into 'dry' diets. The greatest potential lies in the reduction of cost in finishing pig diets and can be achieved by those producers operating wet feeding systems who are prepared to accept a flexible approach to diet formulation, nutrient density and to rationing.

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5

PREDICTING THE ENERGY CONTENT OF PIG FEEDS

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Direct determinations of the digestible (DE) and metabolizable (ME) energy content of pig feeds require lengthy and expensive animal metabolism experiments. Thus routine quality control in feed mills, where data relating to the DE or ME content of feeds are required in hours rather than weeks, is impossible. Considerable interest has therefore been shown in the prediction of DE and ME of feeds, usually by establishing relationships with one or a combination of chemical measurements. Such developments would have additional relevance for mixed feeds if declarations are widened to encompass some aspects of energy evaluation such as DE or ME.

Predictors

Prediction equations have been based upon a number of measurements including proximate analysis, detergent fibre analysis, digested nutrients and physical characteristics. Due to the well established negative influence of crude fibre (CF) on diet digestibility, this term has received considerable attention in the construction of prediction equations. However, as a direct measurement of the indigestible portion of a feed, CF has severe limitations. During its determination, a considerable amount of hemicellulose and lignin (both components of the plant fibre complex and supposedly indigestible by non-ruminants) may become soluble and hence lost from the residue (Van Soest and Robertson, 1977). Such observations have led to new proposals concerning fibre measurement, and the analysis of plant material, based upon differential solubility in various detergent solutions, has been suggested by Van Soest (1970). The three major fractions are neutral detergent fibre (NDF—representing the cell wall), acid detergent fibre (ADF—equivalent to the lignocellulose complex) and acid insoluble lignin (AIL). A modification to ADF (giving MADF) has been proposed by Clancy and Wilson (1966). Buffered acid detergent fibre (BuADF) has been advocated by Baker (1977).

Despite observations that CF is a poor measure of plant fibre, there is no consistent superiority of, for example, NDF, ADF and MADF over CF in

the prediction of either the DE or ME content of compound diets or feedingstuffs for pigs. For example, Drennan and Maguire (1970) found a marginal superiority of MADF over CF while King and Taverner (1975) observed that NDF was slightly superior to both ADF and CF (*Table 5.1*). Morgan, Cole and Lewis (1975), however, suggested that CF was a better predictor of both DE and ME than MADF, and Wiseman (1979) found no real advantage in using detergent fibres compared with CF for cereals (*Table 5.1*).

Table 5.1 EXAMPLES OF CORRELATION BETWEEN EITHER DE OR ME AND FIBRE, TOGETHER WITH EQUATIONS FOR ESTIMATING THE DE CONTENT OF PIG FEEDS FROM THEIR FIBRE CONTENT

Correlation between DE, ME and 'fibre'[a]

	CF	*MADF*	*NDF*	*ADL*	*BuADF*
DE	–0.87	–0.88	–0.82	–0.88	–0.65
ME	–0.87	–0.88	–0.82	–0.89	–0.64

Prediction equations based on fibre[b]

DE (kcal/kg DM) = 4314 – 37.22 NDF% *rsd* = 265, r^2 = 0.543
= 4080 – 52.1 ADF% *rsd* = 283, r^2 = 0.543
= 4129 – 63.98 CF% *rsd* = 308, r^2 = 0.459

[a]From Wiseman (1979)
[b]From King and Taverner (1975)

A possible explanation for these anomalous findings is the inability of any dietary fibre analysis to isolate nutritionally significant fractions. Furthermore, and this point is relevant to the use of prediction in general, equations attempt to assess a biological function (i.e. the digestibility of gross energy) using a mathematical relationship based upon chemical measurements. This may be regarded as a fundamental weakness of their use, and also explains why CF may still be an important component of analysis. It should also be borne in mind that techniques employed in the determination of both x and y variables need to be rigorously standardized, and this usually means their assessment in one centre.

Because of the increase in the number of independent variables, greater success has been achieved when prediction equations have been based on combinations of chemical measurements instead of just one. Usually equations have been based upon proximate analysis (being crude protein (CP), ether extract (EE), nitrogen free extract (NFE), CF and ash). Modifications have included the use of acid ether extract (AEE) in preference to EE as the former is a more complete indication of total fat content of a diet. In addition, the use of NFE has been criticized frequently on the grounds that its method of determination (as a residual after the chemical determination of the other components of proximate analysis) makes it unreliable for inclusion as an independent variable in regression analysis. Consequently, other techniques have been suggested, such as estimating the soluble carbohydrate content of feeds (e.g. Bolton, 1960). Whether these modifications have any advantage in regression analysis, as with the use of different types of fibre analysis, is not yet clear. While in a comparative study, Morgan, Cole and Lewis (1975) indicated a marginal superiority of AEE over EE, there was no real advantage to be gained in using direct determinations of soluble carbohydrate.

There has been interest in the use of digestibility (whether in relation to individual components or combined as total digestible nutrients—TDN) in the prediction of DE or ME. When a move to DE from TDN as a feed evaluation system was recommended for pigs (ARC, 1967), the wealth of data on TDN values that had accumulated, together with a relative paucity of information on DE content, meant that to predict the latter from the former would have been of considerable practical value, particularly in the immediate short term. *Table 5.2* illustrates some of the relationships

Table 5.2 PUBLISHED ESTIMATES OF THE RELATIONSHIP BETWEEN TOTAL DIGESTIBLE NUTRIENTS (TDN) AND DIGESTIBLE ENERGY (DE) OF PIG DIETS (TYPES OF FEEDINGSTUFFS ARE GIVEN IN PARENTHESES)

1 kg TDN =	16.70 MJ/kg DE[a] (compound diets)
	= 18.29 MJ/kg DE[b] (compound diets)
	= 18.41 MJ/kg DE[c] (compound diets)
	= 18.83 MJ/kg DE[d] (compound diets)
	= 18.67 MJ/kg DE[e] (compound diets)
	= 18.49 MJ/kg DE[f] (compound diets)
	= 19.48 MJ/kg DE[g] (compound diets and feedingstuffs)
	= 17.71 MJ/kg DE[h] (cereals)

[a]Maynard, 1953; [b]Schneider, 1947; [c]Swift, 1957; [d]Crampton, Lloyd and McKay, 1957; [e]Zivkovic and Bowland, 1963; [f]Robinson, Prescott and Lewis, 1965; [g]Morgan, 1972; [h]Wiseman, 1979

obtained. However, as the calculation of TDN assumes that 1 unit of digestible crude protein has the same value as 1 unit of digestible nitrogen free extract, then TDN lies closer to ME than DE. Thus, the prediction of DE from TDN is conceptually unsound and would suggest that in the long term DE (and ME) values should be directly obtained. It follows that the crude protein content of a feed will alter the relationship between DE and TDN, and separate equations may need to be used for feeds of varying CP content.

The use of digested nutrients in the prediction of DE or ME (e.g. Nehring, 1969; Thorbek, 1970; Morgan, Cole and Lewis, 1975) has tended to result in greater accuracy, presumably because four independent variables (digestible crude protein, digestible crude fat, digestible nitrogen-free extract and digestible crude fibre) are used. However, the determination of digestibility coefficients requires an identical procedure to that needed for DE or ME, and to predict energy content from digestibility coefficients seems therefore to be of limited relevance. Additionally, there could be considerable errors associated with the use of tabulated values for individual digestibility coefficients. The use of physical measurements including bulk weight and 1000 grain weight has been confined to whole cereals, but with limited success (Bhatty *et al.*, 1974; Christison and Bell, 1975).

Prediction of individual feedingstuffs

It is useful to consider the prediction of the DE and ME content of individual feedingstuffs before discussing compound pig diets. Such procedures were originally suggested as an alternative to the practice of grouping

a wide range of diets and feedingstuffs together for the purpose of formulation of prediction equations. Morgan, Cole and Lewis (1975) obtained the following relationship between DE and CF based on 14 feedingstuffs and three compound diets:

$$\text{DE (kcal/kg DM)} = 4323 - 137\ \text{CF}(\%)$$
$$rsd = 330,\ r^2 + 0.81,\ n = 17 \qquad (1)$$

The accuracy of prediction (in terms of residual standard deviation, *rsd* and r^2) was significantly improved if a group of like feedstuffs was considered. For example, when the three high protein feedingstuffs (soya bean meal, groundnut meal and bean meal) were omitted from the regression analysis the following relationship was obtained:

$$\text{DE (kcal/kg DM)} = 4228 - 140\ \text{CF}(\%)$$
$$rsd = 181,\ r^2 = 0.94,\ n = 14 \qquad (2)$$

Similarly, King and Taverner (1975) observed that the digestibility of the NDF fraction in sweet lupin seed meal was different from that same fraction in other feedingstuffs. The overall relationship obtained was:

$$\text{DE (kcal/kg DM)} = 1.510\ \text{GE} - 2579 - 39.37\ \text{NDF}(\%)$$
$$rsd = 127,\ r^2 = 0.91,\ n = 15 \qquad (3)$$

Eliminating sweet lupin seed meal-based diets improved the accuracy of prediction giving the following equation:

$$\text{DE (kcal/kg DM)} = 1.177\ \text{GE} - 1085 - 40.22\ \text{NDF}(\%)$$
$$rsd = 107,\ r^2 = 0.94,\ n = 11 \qquad (4)$$

These results confirm those of Farrell (1973) who found that the digestibility of cell wall constituents in diets high in fibre was both variable and dependent upon the source of the fibre.

It could be concluded that the approach whereby feedingstuffs of widely differing types are pooled for the purposes of formulation of prediction equations is not valid, and that an improvement in the accuracy of such equations may result if feedingstuffs were to be grouped into specific classes. Initially, cereals were considered by Wiseman and Cole (1980) who presented prediction equations for eight samples of barley and wheat, four of maize and two each of rye and oats. Although the equations derived were of acceptable accuracy when they were applied to only one cereal species, the residual standard deviation was higher than the variability in values determined during animal metabolism trials. It was therefore concluded that recommended DE and ME data for cereals would be more accurate than those derived from prediction equations. A similar conclusion was reached by Batterham *et al.* (1980a) in a study of cereals and wheat by-products, although they did indicate that prediction equations could be useful for weather-damaged cereals.

In general, therefore, prediction equations are of limited application for those feedingstuffs (e.g. cereals) where there is lack of any appreciable

variability in both dependent and independent variables. However, where variability is significant then they may be of considerable value. For example, Batterham *et al.* (1980b) in a study of meat meals, meat and bone meals and bone meals obtained the following equation for DE:

$$\text{DE (MJ/kg)} = -2.97 + 0.77\ \text{GE (MJ/kg)} + 0.020\ \text{EE (g/kg)} + 0.080\ \text{Ca (g/kg)} - 0.159\ \text{P (g/kg)}$$
$$rsd = 0.530,\ r^2 = 0.89,\ n = 14 \qquad (5)$$

However, the same study reported that it was difficult to predict reliably the crude protein digestibility—an important component of feedingstuff quality and one known to be influenced considerably by processing conditions. Processing (used to sterilize, to improve digestibility by altering for example the structure of the polysaccharide molecules, or to denature non-nutritive factors) may also influence markedly the DE or ME content of a feedingstuff, but such a change in nutritive value may not be accompanied by any major change in chemical measurements. For example, Wiseman (1981) in a study of full fat soya beans fed to poultry observed that there was a considerable difference in the directly determined AME of various differently processed products, but that this was not associated with any alteration in proximate analysis. In this context, prediction equations are obviously of limited value.

Prediction of mixed diets

Despite the possible advantages to be gained from considering individual feed ingredients, either separately or in groups of similar materials for the purposes of energy prediction, the use of the values obtained to calculate the DE or ME of a compound diet comprising a number of ingredients can be criticized. These calculated DE or ME values of mixed feeds which are based on individual ingredients will contain all the accumulated errors associated with prediction equations for each ingredient. The feed compounding industry is more interested in equations to estimate the energy content of compound diets. Previous prediction work (Drennan and Maguire, 1970; Morgan, Cole and Lewis, 1975; King and Taverner, 1975) has considered either a combination of both compound diets and individual feedingstuffs, or a relativly small number of compound diets.

At the University of Nottingham School of Agriculture, 99 compound diets for pigs have been analysed for DE and ME content, together with proximate analysis, MADF and GE. These compound diets represented a wide range in value for each of the measurements (*Table 5.3*), although all were representative of commercial practice. Correlation coefficients between measurements are shown in *Table 5.4*. At the outset it was considered inappropriate to include NFE in regression analysis because it is calculated by difference and is not therefore an independent variable; it was also thought invalid to include CF and MADF in the same equation. Prediction equations incorporating various measurements have been determined and these were assessed in terms of residual standard derivations and values for r^2 (the proportion of the variation in the dependent variable

Table 5.3 RANGES IN ENERGY AND CHEMICAL MEASUREMENTS OF 99 COMPOUND DIETS EVALUATED AT THE UNIVERSITY OF NOTTINGHAM AND FORMING THE BASIS OF PREDICTION EQUATIONS USED IN LATER TABLES. (ALL MEASUREMENTS ARE ON A DRY MATTER BASIS)

DE (MJ/kg)	13.78–17.86
ME (MJ/kg)	13.13–17.61
GE (MJ/kg)	17.80–21.87
CP (%)	12.2–28.3
EE (%)	1.0–14.2
CF (%)	2.2– 6.7
MADF (%)	3.5–10.4
ASH (%)	3.2– 9.2
NFE (%)	53.1–73.5

Table 5.4 INDIVIDUAL CORRELATIONS (*r*) BETWEEN ALL MEASUREMENTS FROM THE 99 COMPOUND DIETS PRESENTED IN *TABLE 5.3*

	ME	*GE*	*CP*	*EE*	*CF*	*MADF*	*Ash*	*NFE*
DE	0.974	0.751	–0.045	0.733	–0.274	–0.355	0.126	–0.385
ME	—	0.771	–0.164	0.748	–0.245	–0.330	0.138	–0.329
GE	—	—	–0.316	0.925	0.237	0.141	0.421	–0.631
CP	—	—	—	–0.071	–0.055	0.316	0.346	–0.625
EE	—	—	—	—	0.110	0.045	0.361	–0.659
CF	—	—	—	—	—	0.740	0.089	–0.235
MADF	—	—	—	—	—	—	0.197	–0.285
Ash	—	—	—	—	—	—	—	0.694

accounted for by the equation). However, another important indication of their usefulness, relevant to the feed industry, is the ease of determination of the independent variables (simplicity and time) together with the cost of analysis (equipment, labour and chemicals).

PREDICTION OF DE AND ME USING LINEAR EQUATIONS BASED UPON PROXIMATE ANALYSIS, MADF AND GE

Regression analysis allowed the effect of removing or adding individual independent variables from or to relationships to be determined. Initially, considering just proximate analysis (but replacing CF by MADF), the following equations were derived:

$$\text{DE (MJ/kg DM)} = 16.42 + 0.025\,\text{CP\%} + 0.222\,\text{EE\%} - 0.240\,\text{MADF\%} - 0.77\,\text{ash\%}$$

$$rsd = 0.447,\ r^2 = 0.71,\ n = 99 \qquad (6)$$

$$\text{ME (MJ/kg DM)} = 13.35 - 0.014\,\text{CP\%} + 0.247\,\text{EE\%} - 0.254\,\text{MADF\%} - 0.040\,\text{ash\%}$$

$$rsd = 0.515,\ r^2 = 0.71,\ n = 99 \qquad (7)$$

The original correlation matrix (*Table 5.4*) together with an examination of partial correlation coefficients for all the independent variables in

Table 5.5 PREDICTION EQUATIONS FOR DE AND ME CONTENT OF COMPOUND DIETS WHICH EXCLUDE GE (n = 99 COMPOUND FEEDS)

(a) *Equations based on MADF*							
DE(MJ/kg) =	k	CP	EE	MADF	Ash	*rsd*	r^2
	16.42	+0.025	+0.222	−0.240	−0.077	0.45	0.71
	16.83		+0.216	−0.238	−0.051	0.45	0.69
	16.65		+0.208	−0.247		0.45	0.69
ME(MJ/kg) =	k	CP	EE	MADF	Ash	*rsd*	r^2
	13.35	−0.014	+0.247	−0.254	−0.040	0.52	0.71
	16.11		+0.251	−0.255	−0.055	0.51	0.69
	15.91		+0.242	−0.265		0.52	0.69
(b) *Equations based on CF*							
DE(MJ/kg) =	k	CP	EE	MADF	Ash	*rsd*	r^2
	16.56	+0.014	+0.230	−0.308	−0.101	0.46	0.68
	16.81		+0.227	−0.312	−0.086	0.46	0.68
	16.43		+0.213	−0.318		0.47	0.66
ME(MJ/kg) =	k	CP	EE	MADF	Ash	*rsd*	r^2
	16.45	−0.026	+0.256	−0.337	−0.065	0.53	0.69
	16.07		+0.263	−0.330	−0.093	0.53	0.68
	15.67		+0.248	−0.337		0.54	0.67

equations 6 and 7 suggested that both CP and ash could be omitted with no significant reduction in accuracy (*Table 5.5*). A large proportion of the variation in DE and ME values could therefore be explained in terms of EE and fibre; the use of MADF gave a more accurate fit than CF, although the advantage in using the former was only small.

It may be argued that a more relevant approach when formulating prediction equations for DE and ME is one which at first considers their major determinant, namely gross energy, and then incorporates those factors likely to have a modifying effect. Such an approach of using GE as a predictor has been previously considered by King and Taverner (1975) and Batterham *et al.* (1980a,b). Those components likely to have the major effect of modifying GE are fibre and fat. Accordingly a second series of regression analyses considered the prediction of DE and ME from GE, and subsequently added various components of proximate analysis to the model. The use of GE as the only independent variable produced the following equations:

$$\text{DE (MJ/kg DM)} = 3.233 + 0.671 \text{ GE (MJ/kg DM)}$$
$$rsd = 0.534,\ r^2 = 0.56,\ n = 99 \qquad (8)$$
$$\text{ME (MJ/kg DM)} = 0.295 + 0.790 \text{ GE (MJ/kg DM)}$$
$$rsd = 0.591,\ r^2 = 0.59,\ n = 99 \qquad (9)$$

Both equations indicate that a substantial proportion of the variability in DE and ME could be explained in terms of variability in GE.

Adding individual components of proximate analysis to the two functions (equations 8 and 9 above) produced the equations shown in *Table 5.6*. Introduction of fibre alone (in this case CF was superior to MADF) considerably improved the accuracy of prediction of both DE and ME. The values for residual standard deviations and r^2 of equations based only on GE and CF (being 0.38, 0.77 and 0.43, 0.79 respectively for DE and ME)

Table 5.6 PREDICTION EQUATIONS FOR DE AND ME CONTENT OF COMPOUND DIETS WHICH INCLUDE GE (n = 99 COMPOUND DIETS)

(a) *Equations based on CF*								
DE(MJ/kg) =	k	GE	CP	EE	CF	Ash	*rsd*	r^2
	−2.293	+1.064	+0.035	−0.053	−0.442	−0.191	0.33	0.85
	0.662	+0.986	+0.033		−0.442	−0.185	0.33	0.85
	1.839	+0.862			−0.427	−0.146	0.34	0.83
	2.799	+0.772			−0.424		0.38	0.77
ME(MK/k) =	k	GE	CP	EE	CF	Ash	*rsd*	r^2
	−3.949	+1.157	+0.004	−0.051	−0.483	−0.163	0.39	0.83
	−1.091	+0.994	−0.005		−0.464	−0.157	0.39	0.83
	−1.282	+1.000			−0.463	−0.163	0.39	0.83
	−0.211	+0.899			−0.460		0.43	0.79
(b) *Equations based on MADF*								
DE(MJ/k) =	k	GE	CP	EE	MADF	Ash	*rsd*	r^2
	+0.385	+0.894	+0.046	−0.019	−0.292	−0.150	0.34	0.83
	+1.423	+0.836	+0.045		−0.288	−0.148	0.34	0.83
	+3.018	+0.787			−0.282	−0.097	0.36	0.80
	+3.674	+0.731			−0.296		0.38	0.78
ME(MJ/k) =	k	GE	CP	EE	MADF	Ash	*rsd*	r^2
	−0.929	+0.964	+0.008	−0.012	−0.310	−0.120	0.41	0.81
	−0.270	+0.926	+0.008		−0.308	−0.118	0.41	0.81
	−0.001	+0.918			−0.307	−0.110	0.41	0.81
	+0.740	+0.854			−0.323		0.43	0.79

indicate that such relationships could be acceptable under practical conditions.

The sequential addition of CP, ash and, finally, EE to the models resulted in only a small improvement in accuracy of prediction. In the case of DE, no statistically significant increase in accuracy was obtained with the addition of EE to the equation nor, in the case of ME, with the addition of both CP and EE. There was a minimal contribution of EE in equations based on GE. However, the original matrix (*Table 5.4*) had indicated a very high correlation between EE and GE. There is support, therefore, for the principle outlined earlier that prediction of DE or ME could be achieved simply by considering GE together with a modifying influence (in this case the negative effect of dietary fibre): prediction equations including GE were more accurate than those where it was omitted.

PREDICTION OF DE AND ME USING QUADRATIC TERMS FOR FAT AND FIBRE

In common with previous investigations (King and Taverner, 1975; Morgan, Cole and Lewis, 1975) the current study had isolated certain diets where the predicted value for DE or ME differed considerably from the observed value. A more detailed analysis indicated that there were some diets where the difference was more than twice the residual standard deviation of the prediction equation. Although specific prediction equations isolated specific diets in this way, there was a general trend for those diets high in fibre and high in fat to be overestimated, and for those low in fat to be underestimated.

Such observations might suggest the compilation of separate equations to consider diets whose levels of fat and fibre differed from a narrow range of values. Additionally, the situation may have been responsible for the suggestion, previously discussed, that to use allegedly more sensitive chemical measurements (i.e. the replacement of EE by acid ether extract (AEE) and the use of detergent fibre in preference to CF) would be more valid, although no consistent improvement in the accuracy of prediction has previously resulted from such a move.

A more relevant approach might be one that investigates the role of both fat and fibre in a nutritional context, and then incorporates any observations into general prediction equations. The role of fibre in diet digestibility is well accepted (e.g. Cole, 1974) and the general conclusion is that, due to negative interactions between fibre and other components of the diet, overall diet digestibility is reduced with increasing levels of fibre. It is therefore likely that the response of dietary DE and ME to increasing fibre content is curvilinear (*Figure 5.1a*). The effect of fat level on dietary DE

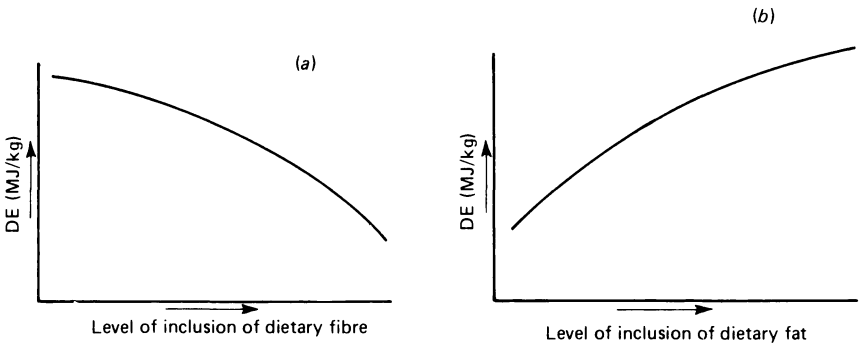

Figure 5.1 Probable effect of dietary fibre (a) and fat (b) on subsequent DE values of a pig feed

and ME content for pigs is less well documented, although evidence from poultry data suggests that successive increments of fat result in progressively smaller increases in overall dietary ME. This 'level of inclusion' effect has been attributed to an interaction between added fat and the basal components of the diet (Mateos and Sell, 1981), which becomes less important with higher levels of fat. Such a situation might be extrapolated to pigs, and the response to added fat, in terms of its effect on dietary DE and ME content, will probably be curvilinear (*Figure 5.1b*). Preliminary (unpublished) work at the University of Nottingham investigating the effect of level of inclusion of two fats has supported such a curvilinear response.

The importance of these two observations in the compiling of prediction equations is that it may be worthwhile including, in regression analysis, quadratic as well as linear terms for both fat and fibre. Accordingly, quadratic terms for EE, CF and MADF have been used in the model to determine if they significantly increased the accuracy of prediction. Following previous observations, GE was also included as an independent variable from the outset.

When considering GE and fibre alone, the following derived equations accounted for 79% of the variation in both DE and ME respectively:

$$\text{DE (MJ/kg DM)} = 2.321 + 0.753\,\text{GE (MJ/kg)} + 0.003\,\text{CF(\%)} - 0.050\,\text{CF}^2\text{(\%)}$$
$$rsd = 0.378,\ r^2 = 0.79,\ n = 99 \qquad (10)$$
$$\text{ME (MJ/kg DM)} = -0.811 + 0.875\,\text{GE (MJ/kg)} + 0.076\,\text{CF(\%)} - 0.063\,\text{CF}^2\text{(\%)}$$
$$rsd = 0.425,\ r^2 = 0.79,\ n = 99 \qquad (11)$$

Both of these equations were significantly ($P<0.05$) more accurate predictors of DE and ME than those equations based only on GE and a linear term for CF (*Table 5.6*), although the improvement in terms of smaller values for *rsd* was only marginal. Adding further variables produced the prediction equations given in *Table 5.7*, and all were marginally more accurate than those that did not include quadratic terms for CF and EE. However, it is apparent from *Table 5.7* that crude protein could be dropped from the equations without significantly reducing their accuracy of prediction. Similarly the inclusion of both EE and $(EE)^2$ appeared to have a negligible effect. The very high correlation between EE and GE has

Table 5.7 PREDICTION EQUATIONS FOR DE AND ME CONTENT OF COMPOUND DIETS WHICH INCLUDE GE AND QUADRATIC EFFECTS OF 'FIBRE' AND EE (n = 99 COMPOUND FEEDS)

(a) *Equations based on CF*

DE(MJ/kg) =	k	GE	CP	EE	$(EE)^2$	CF	$(CF)^2$	Ash	*rsd*	r^2
	+0.747	+0.888	+0.032	+0.134	−0.011	+0.359	−0.092	−0.226	0.30	0.87
	−0.250	+0.877	−0.034			+0.270	−0.081	−0.081	0.31	0.86
	+0.872	+0.825		+0.154	−0.012	+0.373	−0.094	−0.019	0.31	0.86
	+0.960	+0.843				+0.255	−0.080	−0.164	0.33	0.85
	+2.073	+0.759		+0.053	−0.004	+0.021	−0.052		0.38	0.79
	+2.231	+0.753				+0.003	−0.050		0.38	0.79
ME(MJ/kg) =	k	GE	CP	EE	$(EE)^2$	CF	$(CF)^2$	Ash	*rsd*	r^2
	−2.628	+0.984	−0.006	−0.097	−0.008	+0.421	−0.010	−0.020	0.36	0.86
	−2.174	+0.972	−0.005			+0.359	−0.097	−0.179	0.37	0.85
	−2.921	+0.996		−0.093	−0.008	+0.419	−0.104	−0.202	0.36	0.85
	−2.344	+0.976				+0.361	−0.097	−0.185	0.37	0.85
	−1.640	+0.925		−0.015	−0.001	+0.044	−0.060		0.43	0.80
	−0.811	+0.875				+0.076	−0.063		0.43	0.79

(b) *Equations based on MADF*

DE(MJ/k) =	k	GE	CP	EE	$(EE)^2$	MADF	$(MADF)^2$	Ash	*rsd*	r^2
	+1.568	+0.762	+0.041	+0.131	−0.009	+0.094	−0.029	−0.168	0.33	0.84
	+0.957	+0.814	+0.043			+0.028	−0.024	−0.152	0.34	0.83
	+3.767	+0.661		+0.166	−0.010	+0.183	−0.035	−0.125	0.35	0.82
	+2.394	+0.763				+0.088	−0.029	−0.103	0.36	0.81
	+4.478	+0.618		+0.103	−0.006	+0.068	−0.028		0.38	0.79
ME(MJ/k) =	k	GE	CP	EE	$(EE)^2$	MADF	$(MADF)^2$	Ash	*rsd*	r^2
	−0.191	+0.878	+0.005	+0.080	−0.005	−0.049	−0.020	−0.130	0.41	0.81
	−0.591	+0.911	+0.006			−0.090	−0.017	−0.121	0.41	0.81
	+0.066	+0.866		+0.084	−0.006	−0.039	−0.020	−0.125	0.41	0.81
	−0.381	+0.904				−0.081	−0.017	−0.114	0.41	0.81
	+0.780	+0.823		+0.020	−0.001	−0.153	−0.013		0.43	0.79
	+0.492	+0.843				−0.165	−0.012		0.48	0.79

already been commented upon; however, the failure of a quadratic term for EE to improve markedly the accuracy of the prediction equations is somewhat surprising, particularly in view of the suggestion that the relationship between DE or ME and EE is curvilinear. There is ample evidence in studies with poultry, that in addition to being influenced by level of inclusion, the ME of a specific fat is also dependent upon its structure. This observation probably applies equally to pigs. The response to added fat is therefore confounded by type of fat as well as inclusion level, and therefore the use of EE (which measures fat *per se*) may not be a sufficiently accurate measurement.

The series of prediction equations presented in *Tables 5.5, 5.6* and *5.7* indicate the mathematical accuracy that is associated with the prediction of DE and ME content of pig feeds from a number of combinations of chemical measurements. Decisions as to which ones to use will obviously rest with individual circumstances. Accuracy is of major importance, but it could be that a small reduction in accuracy is more than offset by a considerable improvement in speed of analysis and/or a reduction in cost, if functions are based only upon those chemical measurements that account for the bulk of the variation in DE and ME values. In this context, prediction equations based upon GE, CF,$(CF)^2$ and ash would appear to be particularly useful.

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6

THE USE OF FAT IN SOW DIETS

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Piglet survival is of utmost importance in swine production. Numerous studies (e.g. Bereskin, Shelby and Cox, 1973) have shown that about 25% of the pigs born alive in the USA die before weaning, and the majority of these deaths occur during the first few days after birth. Two of the major causes of piglet mortality are crushing by the sow and weakness which is probably brought about by chilling, starvation and dehydration (Fahmy and Bernard, 1971; Zimmerman, 1978). It is quite apparent that preweaning mortality is a major cause of loss to the swine industry, and that efficiency of production could be greatly enhanced if mortality could be reduced.

Recently, a major topic of research has been the addition of fat to sow diets during late gestation and lactation in an attempt to improve the survival of newborn pigs. This work was stimulated by the original research of Seerley *et al.* (1974). In their studies, pig survival to 21 days was increased when corn oil was added to the diet of sows from the 109th day of pregnancy to parturition.

Why is piglet mortality so high and what changes occur?

Newborn pigs are vulnerable to cold stress because of their sparse hair coats, thin hides, and small amounts of body fat. Percentages of body fat are 1 to 2% (Manners and McCrea, 1973; Seerley and Poole, 1974; Okai, Aherne and Hardin, 1977; Lodge, Sarkar and Kramer, 1978; Boyd *et al.*, 1978b) and only 5–10 g of fat are utilized during starvation (Seerley and Poole, 1974; Scerley, Griffin and McCampbell, 1978a) with an estimated caloric utilization of 0.69 MJ/day (Seerley, 1981).

Because of poor insulative protection piglets often become chilled, and may have difficulty maintaining body temperature. An increase in body fat would improve this situation and might increase survival. Several studies (Seerley *et al.*, 1974; Seerley, Griffin and McCampbell, 1978a, b; Okai, Aherne and Hardin, 1977; Boyd *et al.*, 1978b; Seerley, Snyder and McCampbell, 1981) have shown a consistent but generally non-significant

increase in body fat of newborn pigs from sows fed fat; this increase in body fat should improve the pigs' insulative protection.

At the time of birth, piglets have a source of readily available energy stored as glycogen in liver, heart and muscle, but these stores are depleted rather rapidly after birth (Morrill, 1952; Seerley and Poole, 1974; Seerley, Griffin and McCampbell, 1978a; Seerley, Maxwell and McCampbell, 1978; Okai, Aherne and Hardin, 1978; Boyd *et al.*, 1978b) (*Table 6.1*). As the glycogen is depleted, the pig must receive an external source of energy or the level of circulating blood glucose will fall dramatically. If the blood glucose drops to a certain level the piglet develops a condition called hypoglycaemia, which leads to weakness and predisposition to be overlain

Table 6.1 RATE OF LIVER GLYCOGEN DISAPPEARANCE IN PIGLETS FROM BIRTH THROUGH 24 h OF AGE

Hour of sacrifice	*No. of piglets*	*Glycogen concentration* (mg/g)	*% of 0 h*
0 (birth)	12	177.87	—
6	12	87.25	49.1
12	12	73.04	41.1
24	12	25.39	14.3

From Boyd (1978b)

Table 6.2 RATE OF LIVER GLYCOGEN DISAPPEARANCE IN THE PIGLET FROM BIRTH THROUGH 24 h, WHEN SOWS WERE FED FAT OR CORN STARCH[a]

Hour of sacrifice	*No. pigs per treatment*	*Control*[b]	*Control + tallow*[c]	*Control + corn starch*[d]	*SE*
		(mg glycogen/g wet liver tissue)			
0 (birth)	4	174.9	188.7	170.0	9.55
6	4	77.8	93.9	90.0	24.64
12	4	62.7	95.6	60.8	14.13
24	4	20.2	22.6	33.4	7.02

From Boyd (1978b)
[a]Diets fed from day 100 of pregnancy to parturition.
[b]Corn–SBM 14% protein, feeding rate 1.8 kg/head/day.
[c]Tallow added at 20% of the diet.
[d]Fed to the same energy intake as the tallow diet.

by the sow. Frequent nursing soon after birth will prevent this sequence of events, and help to maintain the blood glucose at a normal level. The newborn pig is, therefore, dependent not only upon stored energy, but also upon energy acquired by suckling. Nevertheless, to improve piglet survival it would appear beneficial to increase the energy stores at birth.

Tallow, added to the sow's diet at the rate of 20% and fed from day 100 of pregnancy to parturition, produced a slight but non-significant increase in piglet liver glycogen at birth, and this difference was maintained throughout 12 h after birth (*Table 6.2*). Corn starch fed at the same energy intake as tallow maintained a high glycogen level at 6 h but not at 12 h. These data are consistent with those of Seerley *et al.* (1974) who fed corn oil five days before farrowing with a resulting increase in body glycogen of the piglet at birth. Thus, it would appear that the extra glycogen at birth

and its longer retention may be one beneficial factor for improving the survival of piglets from sows fed fat. Several authors (Seerley *et al.*, 1974; Cast *et al.*, 1977; Boyd *et al.*, 1978b, 1981; Parsons, 1979) have found that piglets from sows fed diets with added fat have higher blood glucose concentrations than those of piglets from control sows for up to 24 h after birth, although just the opposite was reported by Friend (1974).

Kasser *et al.* (1981) fed sows fat or corn starch during the last five weeks of gestation. Glucose clearance rates decreased with increasing levels of dietary fat and increased with increasing levels of dietary starch. Serum free fatty acid concentrations were higher in sows fed fat prior to and during the clearance of glucose in comparison to sows receiving corn starch diets, thus increasing the amount of glucose available to the fetus by decreasing maternal tissue glucose clearance. The effect of supplemental energy, as carbohydrate or fat fed to sows during late gestation, on energy storage and glucose homeostasis in neonatal pigs was studied by Boyd *et al.* (1981). The effect of energy source was evaluated by fasting piglets from birth or after nursing for 24 h. The energetic status of fasting, newborn pigs was enhanced slightly when the sow's diet contained tallow. Thus, adding fat to the sow's diet is one possible way of improving piglet energy stores.

The energy supply from glycogen is shortlived, and it is crucial that piglets start suckling regularly as soon as possible. For many years herdsmen have equalized litter size by transferring piglets from one sow to another in order to reduce competition in large litters and equalize milk intake. Another way to ensure adequate energy nutrition is by increasing the energy level of the milk and by increasing milk yield. Milk fat and energy are relatively low in early milk, but feeding fat to sows appears to be consistent in increasing the fat content of the colostrum and milk (Peo, 1978; Seerley, 1981). Four studies (*Table 6.3*) have shown an increase in

Table 6.3 MILK YIELDS OF SOWS FED FAT (kg/day)

Reference	*Control*	*+ Fat*
Kruse *et al.* (1977)	4.60 (9)[a]	5.33 (15)
Pettigrew (1978)	3.82 (10)	4.48 (18)
Coffey, Seerley and Mabry (1981)	5.48 (10)	7.33 (10)
Boyd *et al.* (1982)	8.72 (12)	9.44 (12)

[a]No. of litters in parentheses

milk yield, while Lellis and Spear (1981) reported no significant response when sows were fed fat. The increase in colostrum and milk fat as well as the increase in milk yield provides a more adequate energy supply for the newborn pig which will aid in replenishing its rapidly declining energy stores.

Does added fat improve piglet survival?

Since the work of Seerley *et al.* (1974) there have been many experiments to evaluate the effect of fat added to sow diets on piglet survival. A summary of these experiments is presented by Moser and Lewis (1980)

Table 6.4 RESULTS OF EXPERIMENTS THAT HAVE EXAMINED THE EFFECT OF

Reference	*State or country*	*Fat in diet*		*Days fed*		*No. of*[a] *litters*	*No. pigs born alive*	*Pigs alive at 21 d*
		Type	*%*	*Before farrowing*	*After farrowing*			
Okai *et al.* (1977)	Canada	Tallow	10	14	0	21	9.3	8.4
Kruse *et al.* (1977)	Denmark	Soybean oil	2	114	21	9	9.1	7.4
			4	—	—	—	—	—
Seerley *et al.* (1974)	Georgia	Corn oil	40	5	0	27	9.4	7.1
Seerley *et al.* (1976)	Georgia	Lard	40	5	21	5	—	—
Seerley *et al.* (1981)	Georgia	Corn oil or animal fat	10	5	21	32	11.2	8.8
Pettigrew (1978) 1	Commercial company	Corn oil	5	40	0	13	—	—
				0	35	—	—	—
				40	35	—	—	—
2		Corn oil	5	5	21	21	—	—
			10	—	—	—	—	—
3		Corn oil or animal fat	6	5	14	20	—	—
Allee and Salava 1 (1978)	Kansas	Tallow	6	14	14	11	9.1	8.5[c]
2		White grease or tallow	6	0	21	44	9.0	7.9
Bishop *et al.* (1979)	Kentucky	Soybean oil	23	9	0	40	9.7	8.0[c]
Stahly *et al.* (1980)	Kentucky	Safflower oil or oleinite	10	0	21	34	9.8	8.2
Parsons (1979)	Michigan	Tallow	7.5	5	21	10	8.8	7.1
			15	—	—	—	—	—
			10	—	—	—	—	—
Cornelius (1980) 1	Minnesota	White grease	10	10	14	12	11.4	9.4[d]
2		White grease	10	5	14	12	10.8	9.3[d]
Boyd *et al.* (1978a) 1	Nebraska	Tallow	20	14	0 or 14	22	7.0	5.7[c]
2		Tallow	20	0 or 14	14	38	8.3	6.6[c]
Boyd *et al.* (1982)	Nebraska	Tallow	8	14	21	94	9.3	8.5
Cast *et al.* (1977)	Nebraska	Tallow	15	5	14	23	9.8	8.0[e]
Danielson *et al.* (1978)	Nebraska	Tallow	8	5	21	28	10.6	7.9
Moser *et al.* (1978)	Nebraska	Tallow	15	5	14	38	11.5	9.4[c]
Pollmann *et al.* (1979)	Nebraska	Tallow	8	24	14	115	11.3	8.3[c]
Libal and Wahlstrom (1979)	South Dakota	Yellow grease	10	7	21	9	8.8	5.9
Wahlstrom and Libal (1976)	South Dakota	Corn oil	5	30	7	15	9.9	8.1
Cieslak *et al.* (1980)	Wisconsin	White grease	15	5	21	43	10.4	8.3

[a]Fat content of colostrum and milk was often not analyzed in all litters.
[b]35 day data.
[c]14 day data.
[d]28 day data.
[e]Adjusted 14 day data.
[f]Difference between control and + fat $P<0.05$.
[g]Difference between control and + fat $P<0.01$.

(*Table 6.4*). Some results have been condensed and some individual trials combined to make the data more manageable. Where possible, the values chosen for the 'control' treatment were those of sows fed an equal amount of energy from a different source, for example corn starch. It is clear from *Table 6.4* that a wide variety of experimental designs has been used. The type of fat has varied from corn and soybean oils to tallow and lard; the

SUPPLEMENTAL FAT IN SOW DIETS (FROM MOSER AND LEWIS, 1980)

Control								*+ Fat*				
Survival (%)	*Avg. birth wt* (kg)	*Avg. 21 d* wt (kg)	*Fat in colos-trum* (%)	*Fat in milk* (%)	*No. of*[a] *litters*	*No. pigs born alive*	*Pigs alive at 21 d*	*Survi-val* (%)	*Avg. birth wt* (kg)	*Avg. 21 d wt* (kg)	*Fat in colos-trum* (%)	*Fat in milk* (%)
90.3	1.45	5.41	6.2	—	20	10.3	9.4	91.3	1.36	5.19[f]	7.1	—
81.3	1.37	5.20	5.6	6.8	9	8.0	6.7	83.8	1.41	5.80	5.5	7.8
—	—	—	—	—	7	8.6	7.2	83.7	1.25	5.10	6.1	7.9
75.2	1.20	5.12	5.7	7.1	32	9.6	8.6	89.9	1.30	5.27	8.2[f]	7.6
80.0	—	—	—	—	5	—	—	83.0	—	—	—	—
78.5	1.20	4.60	8.5	7.3	64	10.1	9.1	89.7[f]	1.35	5.15	8.3	8.6
78.1[b]	—	—	5.6	6.8	12	—	—	83.4[b]	—	—	9.1	7.6
—	—	—	—	—	13	—	—	80.1[b]	—	—	9.2	7.5
—	—	—	—	—	13	—	—	85.2[b]	—	—	9.8	8.0
81.8	—	—	8.1	—	22	—	—	86.2	—	—	9.4	—
—	—	—	—	—	22	—	—	88.6	—	—	8.8	—
82.0[c]	—	—	7.0	6.2	37	—	—	71.2[c]	—	—	8.8	8.1[f]
93.0[c]	1.24	3.46[c]	—	—	12	8.8	8.3[c]	94.3[c]	1.13	3.32[c]	—	—
88.0	1.29	5.31	—	—	44	9.8	8.8	89.9	1.30	5.39	—	—
87.5[c]	1.32	3.93[c]	5.0	—	38	9.0	7.5[c]	85.2	1.32[c]	3.86[c]	6.5[f]	—
84.5	1.44	5.96	—	7.2	68	10.6	8.7	84.2	1.35	5.89	—	9.5[g]
80.7	1.47	—	—	4.1	10	8.8	8.2	93.2	1.53	—	—	5.2
—	—	—	—	—	10	9.1	8.2	90.1	1.47	—	—	6.2
—	—	—	—	—	8	7.5	6.6	88.0	1.45	—	—	6.0
82.1[d]	1.36	6.99[d]	—	—	12	11.3	9.4[d]	82.9[d]	1.41	6.62[d]	—	—
87.0[d]	1.54	7.03[d]	—	—	12	10.8	8.7[d]	80.0[d]	1.45	6.35[d]	—	—
83.2[c]	1.51	4.29[c]	5.6	9.7	22	9.3	6.6[c]	72.7[c]	1.17	3.45[c]	8.9	9.4
79.2[e]	1.40	3.92[e]	7.6	8.3	36	8.3	6.7[e]	81.6[e]	1.31	3.80[e]	6.6[f]	11.0[f]
92.5	1.53	6.12	9.6	13.2	94	9.1	8.5	94.0	1.50	6.34	13.2[f]	15.8
83.3[e]	1.40	4.54[e]	6.0	7.2	71	9.2	8.3[e]	88.6[f]	1.42	4.27[e]	8.6[f]	9.8[f]
74.5	1.33	5.03	—	—	29	11.0	8.3	75.5	1.32	5.16	—	—
81.7[c]	1.57	3.90[c]	—	—	36	10.4	8.9[c]	85.6[c]	1.54	4.10[c]	—	—
73.6[c]	1.43	3.82[c]	—	—	115	11.4	8.6[c]	75.2[c]	1.42	3.93[c]	—	—
67.0	1.59	6.30	—	—	8	8.4	5.6	66.7	1.50	5.58	—	—
80.8	1.38	4.92	—	—	15	9.2	7.8	84.8	1.59	4.45	—	—
79.1	1.36	5.93	—	—	42	9.8	8.7	84.9[f]	1.35	6.22[f]	—	—

level of fat has varied from 2 to 40%; and the number of days of feeding fat has varied from as few as five to as many as 135. In view of the wide range of conditions employed, any general statements about the effect of added fat must be made with caution, but there now appears to be sufficient data available to allow certain conclusions to be drawn.

In all of this work, the area of least controversy is the effect of fat added to sow diets on the fat content of milk and colostrum. Almost all researchers who have analyzed milk have reported elevated fat contents of milk and colostrum of sows fed added fat. In many cases the increase has been substantial and has been statistically significant.

In contrast, the question of a beneficial effect on piglet survival and consequent litter size at weaning has been the subject of a great deal of

Table 6.5 OVERALL SUMMARY OF EXPERIMENTS WHERE FAT WAS FED TO SOWS[a]

	Control	*(No. of litters)*	*+ Fat*	*(No. of litters)*	*Difference*
Pigs born alive/litter	10.0	(677)	9.9	(814)	−0.1
Pigs weaned/litter	8.1	(677)	8.4	(814)	+0.3
Survival (%)	82.0	(736)	84.6	(938)	+2.6
Avg. birth wt (kg)	1.41	(677)	1.39	(814)	−0.02
Avg. 21 d wt (kg)	5.57	(356)	5.66	(432)	+0.09
Fat in colostrum (%)	7.3	(360)	9.1	(512)	+1.8
Fat in milk (%)	9.1	(322)	10.1	(506)	+1.0

[a]Data are weighted for the numbers of litters involved in each experiment

controversy. As shown in *Table 6.4*, there is much variation both within and between experiments in the parameters relating to pig numbers and weights. An overall summary of these results is presented in *Table 6.5*, which includes the total number of litters involved in each comparison. It is clear that there was little or no effect of dietary fat on litter size at birth. There was, however, a 2.6% increase in piglet survival, which resulted in an increase in litter size at weaning of 0.3 piglets. The data in *Table 6.5* also illustrate that overall, dietary fat had little or no effect on average piglet weight at either birth or weaning. The 0.3 piglet increase in litter size at weaning is small enough but it is hard to prove or disprove with a single experiment. Approximately 700 sows per treatment are needed to obtain a good chance of detecting a statistically significant difference of this size (Cochran and Cox, 1957). No experiment to date has even approached that number. Thus, one would expect no response or a negative response to be recorded in some experiments. Nevertheless, an increase of 0.3 piglet is of appreciable economic significance to a pork producer. A critical question that arises therefore is: was the 0.3 piglet increase in litter size at weaning due to the added fat or did it occur by chance? Although it is not possible to provide an unequivocal answer to this question, there is evidence that the difference was indeed due to the added fat. In *Table 6.4* there are a total of 31 comparisons of the survival of piglets from sows fed fat with the survival of piglets from control sows. Twenty-five of these comparisons showed a positive response and six a negative response. The likelihood of this occurring by chance was tested by using the sign test (Snedecor and Cochran, 1967). The test revealed that the likelihood of 25 to 31 comparisons being positive by chance was less than 1 in 100 ($P<0.01$).

Although the current evidence seems to merit the cautious conclusion that overall the addition of fat to sow diets does increase piglet survival, the fact that some experiments have found little or no response cannot be ignored. Some negative results would be expected for the reasons outlined above, but it is important to examine which factors increase the likelihood of a positive response.

What factors are important?

The type of fat used seems to be relatively unimportant. Unfortunately, it is not possible to separate type of fat from level, but at present there are no

Table 6.6 EFFECT OF LEVEL OF FAT ADDED TO THE DIET OF SOWS (VALUES SHOW THE DIFFERENCE BETWEEN THE + FAT AND THE CONTROL TREATMENTS)

Parameter	*Level of fat added (%)*		
	<7.5	*7.5 to 15*	*>15*
Pigs weaned/litter	−0.1 (5)[a]	+0.2 (15)	+0.5 (4)
Survival (%)	+2.0 (10)	+3.8 (16)	+1.5 (5)

[a]No. of experimental comparisons.

data to indicate that one type is better than any other. Liquid vegetable oils have advantages in terms of ease of handling, but animal fats are usually less expensive.

A summary of the effect of level of fat on piglets weaned per litter and survival is presented in *Table 6.6*. Most experiments have used fat levels between 7.5 and 15% and this is the range that has given the greatest response in survival. The number of piglets weaned per litter was maximized by levels greater than 15%, but this is based on only four experiments. In one of these (Boyd *et al.*, 1978a) there was a 2.3 piglet difference in the number of piglets born alive. If this experiment is removed, then the means for the experiments with levels greater than 15% fat are: piglets weaned per litter + 0.4, survival + 4.5%. Thus, based on the limited data available, it seems that a minimum of 7.5% fat should be added, and that there is little advantage of using levels greater than 15%.

Another variable, which may influence the likelihood of a positive response, is the length of time of feeding fat. The results available to date are somewhat confusing in this regard (*Table 6.7*). In terms of the number

Table 6.7 EFFECT OF THE PERIOD OF FEEDING FAT TO SOWS (VALUES SHOW THE DIFFERENCE BETWEEN DIETS WITH ADDED FAT AND THE CONTROL TREATMENTS)

Parameter	*Gestation only*	*Lactation only*	*Gestation + lactation*
Pigs weaned/litter	+0.7 (3)[a]	+0.7 (2)	0.0 (17)
Survival (%)	+4.7 (4)	+1.2 (3)	+3.4 (22)

[a]No. of experimental comparisons.

of piglets weaned per litter, it appears to be more beneficial to add fat either in late gestation or lactation rather than both periods. But, in terms of survival (which removes differences due to the number of piglets born alive), feeding during gestation alone or during gestation and lactation gave similar advantages over feeding during lactation only. Adding fat during both periods increases the fat content of both colostrum and milk. If it is reasonable to assume that this is advantageous to the suckling piglet, then both periods may be desirable. From a practical point of view, one scheme that works well is to move sows to their farrowing quarters seven days before farrowing, and to begin feeding a lactation diet with added fat at that time. Pettigrew (1981) suggested that at least 1 kg of fat should be fed to the sow before farrowing. Feeding a diet with 10% added fat for seven days before farrowing will achieve this goal.

Two additional factors, which may influence the results, are the survival rate of the controls, and the average birth weight of the piglets. As Pettigrew (1981) pointed out, there is less potential for improving survival when the survival of piglets from control sows is 90% than when it is 70%. It is well known that there is a positive correlation between birth weight and survival in baby pigs. In data reported by Zimmerman (1978) the survival rate increased from 42% for piglets weighing less than 0.9 kg at birth to 88% for piglets weighing 1.8 kg or more. Most studies that have reported an increase in overall survival of the litter due to the feeding of fat to the sow have shown a marked improvement in the survival of the smaller pigs in the litter (Seerley *et al.*, 1974; Cast *et al.*, 1977; Boyd *et al.*, 1978a; Cieslak, Liebbrandt and Benevenga, 1980; Seerley, Snyder and McCampbell, 1981). Thus under conditions that predispose to low birth weights there may be a tendency to show a greater response to added fat.

Is adding fat economically advantageous?

One of the limiting factors associated with adding fat to pig diets is economics. The question being asked is: if there is a positive response to adding fat to sow diets, will it pay? Because fat costs more than cereals, adding fat will increase the cost of the diet and thereby add to the total cost per litter. The data summarized in *Table 6.5* indicate that adding fat results in an increase in pigs weaned of about 0.3 pig/litter. But, is this economical? It is impossible to derive an economic example that will apply in every situation. In order to answer this question individuals must develop their own costs and returns. However, Moser and Lewis (1980) presented one example which indicates that a 0.3 piglet/litter improvement in piglet survival is large enough to more than offset the increase in feed cost by the addition of fat to the sows' diet.

Conclusion

When all of the available data are considered together, there is evidence that adding fat to sow diets can improve piglet survival. The improvement is small, and has not been observed in all experiments, but does appear to be large enough to more than offset the increased feed cost. The slight increase in glycogen stores and body fat at birth may increase the piglet's chances of survival, but the most important factor may be the increased energy intake of the newborn pig as a result of the increase in the fat content of the colostrum and milk, and the increase in milk yield. More research is needed to define the feeding regimen necessary to maximize piglet survival. Results of individual studies on adding fat to sow diets must be evaluated in the light of all the existing data; meaningful conclusions, either positive or negative, cannot be drawn from single experiments with relatively small numbers of sows.

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7

VITAMIN RESPONSIVE CONDITIONS IN BREEDING PIGS

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Introduction

The vitamins represent only a tiny percentage of the diet fed to the reproducing female, but nevertheless they are essential to the health and well being of the animal. The B-vitamins act as co-factors in enzyme systems, catalysing metabolic processes and, as a consequence, exert an important and often rate limiting effect on almost all aspects of intermediary metabolism. The fat soluble vitamins, together with ascorbic acid, are involved in tissue differentiation and the maintenance of tissue integrity. A number of vitamins are essential for the maintenance and efficient operation of the pig's immune system, being required for the production of immunoglobulins and for the protection of leucocytes. It follows that an inadequate supply of a vitamin may seriously impair a metabolic function and that this in turn may have physiological consequences which can affect productivity. The problem facing the nutritionist is to decide the level of vitamin provision which represents an adequate supply and to ensure that this level is obtained by the animal. The complexity of vitamin action and interaction and the paucity of reliable data on which to base allowances make this at best a daunting task and at worst a near impossibility.

A model for the derivation of vitamin allowances

The assessment of the animal's requirement for a vitamin is fraught with difficulties. Many so-called vitamins consist of not one but a number of closely related compounds possessing varying degrees of vitamin activity (*Table 7.1*). The relative activity of these related compounds can vary between species and in some cases the animal's needs may only be effectively met by one of the compounds.

In some instances the animal's requirement for an active form of the vitamin may be met totally by the provision of an appropriate precursor from which the animal can synthesize the active compound. In other cases synthetically produced analogues can satisfactorily substitute for the

Table 7.1 FAT SOLUBLE VITAMINS AND NATURALLY OCCURRING VITAMIN ACTIVE COMPOUNDS

Generic descriptor	*Name of parent compound*[a]	*Name of vitamin-active compounds*
Vitamin A	Retinol	Retinol (vitamin A_1 alcohol) Retinal (vitamin A_1 aldehyde) Retinoic acid (vitamin A_1 acid) Dehydroretinol (vitamin A_2) Provitamin A:[b] α-carotene β-carotene γ-carotene Chryptoxanthine
D	Cholecalciferol	Cholecalciferol (vitamin D_3) Ergocalciferol (vitamin D_2) 1,25-Dihydroxycholecalciferol 1,25-Dihydroxyergocalciferol
E	α-Tocopherol	α-, β-, γ-, δ-Tocopherol α-, β-, γ-, δ-Tocotrienol
K	Phylloquinone	Phylloquinone (vitamin K_1) Menaquinone (vitamin K_2) Menadione (vitamin K_3)

(After Christensen, 1981)
[a]According to *J. Nutr.* (1978) **108**, 7–12
[b]1 mg of β-carotene is equivalent to 533 IU vitamin A, but only when supplied in amounts equal to maintenance requirements. In greater amounts the vitamin A activity is less.

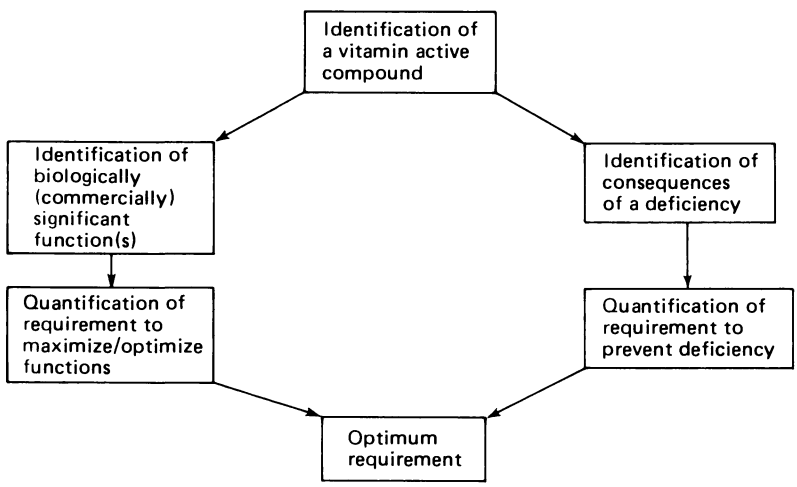

Figure 7.1 Schematic representation of stages in the determination of a vitamin requirement

naturally occurring compound. Active forms of vitamins may not exist in free states within nature but as salts, some of which are 'available' to the animal and therefore biologically active. Other forms may be extremely stable rendering the active component 'unavailable' to the biological system.

Ideally the identification of a vitamin requirement would follow the steps outlined schematically in *Figure 7.1*. The first stage would be the identification of the active form of the compound and activity of related compounds. In order to arrive at a requirement value it is then necessary to identify:

(1) the clinical symptoms of a vitamin deficiency (avitaminosis) and demonstrate that such symptoms can be reversed or prevented by an adequate provision of the vitamin in the diet of the animal;
(2) other functions of biological and/or commercial significance which may be influenced by the level of supply of the vitamin.

These two approaches may be identical if, for example, the only identifiable function of the vitamin is the alleviation/prevention of a deficiency symptom. However, because of the complex nature of vitamin action a number of different functions may be fulfilled at different levels of vitamin supply.

The action of vitamin E provides a good example of this. Vitamin E consists of two sub-families, the tocols and the trienols which differ in the degree of unsaturation of the phytol chain. Each of these groups is further divided into alpha, beta, gamma and delta forms depending upon the position of the methyl group on the cromanol ring (*Table 7.2*).

The situation is further complicated by optical isomerism. While natural feedstuffs contain only the D form of the compounds, commercially available sources contain mixtures of both the optical isomers. The various tocopherols, tocotrienols and their optical isomers have different biopotencies (Sebrell and Harris, 1972) (*Table 7.3*).

Table 7.2 STRUCTURES AND NAMES OF NATURALLY OCCURRING TOCOLS AND TOCOTRIENOLS

Position of methyl groups	*Trivial name (abbreviations)*	
	Tocol structure	*Tocotrienol structure*
5,7,8	α-tocopherol (α-T)	α-tocotrienol (α-T-3)
5,8	β-tocopherol (β-T)	β-tocotrienol (β-T-3)
7,8	γ-tocopherol (γ-T)	γ-tocotrienol (γ-T-3)
8	δ-tocopherol (δ-T)	δ-tocotrienol (δ-T-3)

(After Ullrey, 1974)

Table 7.3 RELATIVE BIOPOTENCY OF NATURAL FORMS OF VITAMIN E

Natural form	*Relative biopotency*
α-tocopherol	100
β-tocopherol	15–40
γ-tocopherol	3–19
δ-tocopherol	<1
α-tocotrienol	17–21
β-tocotrienol	1–4

(Sebrell and Harris, 1972)

Recent studies reported by McMurray and Rice (1982) suggest that of the various forms only D-α-tocopherol is of significance in the case of the pig. In their study a fortified barley soya diet was fed which contained a normal mixture of tocopherols and tocotrienols. However, while they found abundant quantities of α-tocopherol in tissues, there was little evidence of any of the other homologues. Although confirmatory evidence is necessary, this strongly suggests that of the compounds grouped under the generic term 'vitamin E' only one, D-α-tocopherol, is of major significance in the nutrition of the pig.

A deficiency of vitamin E produces a number of characteristic yet overlapping lesions observed post mortem in young pigs. The conditions have been variously described as dietary liver necrosis (hepatosis dietetica), nutritional muscular dystrophy, mulberry heart disease, dietetic microangiopathy, acute circulatory failure, yellow fat disease and respiratory distress (Whitehair and Miller, 1975; Rice and McMurray, 1982). A review of the literature (Agricultural Research Council, 1981) would suggest that in order to avert such deficiency symptoms the minimum dietary requirement of growing pigs receiving diets containing about 35 g total fat/kg would be 8 mg D-α-tocopherol/kg DM for pigs up to eight weeks of age and 5 mg D-α-tocopherol/kg DM thereafter. However, it has been shown that vitamin E fulfils two other significant functions when included in the diet at higher levels. There is evidence in a number of species that vitamin E stimulates immune responses (Nockels, 1979). Although evidence in the pig is limited there are studies which indicate that large injections of α-tocopherol (160–300 mg) significantly increase antibody titres and thereby increase resistance to disease (Heinzerling *et al.*, 1974).

More recently Ellis and Vorhies (1976) found that supplementation of the diet with DL-α-tocopherol was also effective in improving antibody production. In their trial the control animals were fed a diet containing 10 mg D-α-tocopherol and experimental diets were supplemented with 28 or 100 mg D-α-tocopherol/kg and the pigs injected with *E. coli* bacteria. The pigs supplemented with 100 mg D-α-tocopherol developed anti-*E. coli* serum antibody titres two to three times greater than those of the control animals, whilst pigs receiving an additional 28 mg D-α-tocopherol had intermediate titres. Thus it would appear that the inclusion of α-tocopherol in the diet at a level considerably in excess of that needed to prevent overt deficiency symptoms increases the animal's capacity to resist a disease challenge.

Results from other species confirm that dietary additions of α-tocopherol are effective in stimulating the immune response but that the chemical form of tocopherol significantly affects the level of response obtained (Nockels, 1979). This being the case there is a need for more extensive research on this phenomenon and its application in pig production.

The second response to tocopherol at levels in excess of that required to fulfil the 'normal' dietary requirement is in respect of its antioxidant role. This subject has been reviewed by Marusich (1979) and by an Agricultural Research Council Working Party (Agricultural Research Council, 1981). Pork is particularly susceptible to fatty acid oxidation which has an adverse

Table 7.4 EFFECT OF FEEDING GRADED CONCENTRATIONS OF VITAMIN E TO SWINE

Parameter	*Vitamin E* (IU/head/day) *for last 32 days prior to slaughter*			
	0	*50*	*100*	*200*
Vitamin E (μg/g) back fat	5.2	6.9	9.4	9.4
Vitamin E (μg/g) lard	4.6	5.9	8.4	9.9
TBA number[a]—back fat	11.7	9.0[b]	6.2	3.9
TBA number—lard	10.8	6.6	5.2	3.9
Induction period[c] (days)—back fat	5.3	5.2[b]	7.2	7.8
Induction period (days)—lard	4.8	6.5	6.8	8.8

(Hvidsen and Astrup, 1963)
[a]TBA number is a measure of malonaldehyde present in the tissue using 2-thiobarbituric acid (TBA). The higher the TBA value, the greater the oxidative rancidity of the meat.
[b]Only values not statistically significant at the 5% level when compared to control ration.
[c]Induction period = time taken for fat to reach a Peroxide Value of 20 when held in a beaker (20 ml) in an incubator at 55 °C.

effect upon its keeping quality and palatability. A number of reports from Scandinavia have confirmed that α-tocopherol supplementation of meat pigs prior to slaughter increases pork tissue stability and palatability. The tocopherol level in pork fat and hence its stability increases in proportion to the dietary concentrations (*Table 7.4*). From a series of Norwegian trials Astrup (1973) concluded that there was no upper limit observed when vitamin E was used as a stabilizing agent and that the higher the level used the better the results obtained.

Thus when considering the 'requirement' of an animal for a vitamin it is necessary to identify which function or functions are being considered. In the example that has been used 10 mg D-α-tocopherol/kg diet might be considered adequate as the 'requirement' to avert clinical deficiency lesions, whereas the 'requirement' for optimum function of the immune system might be ten times greater than this and the 'requirement' for maximum pork stability 20 times greater. Having assessed the 'requirement' of the animal for a vitamin active compound for the known, significant functions the nutritionist still has to convert this 'requirement' into an 'allowance'. The factors to be considered in taking such a decision are outlined in *Figure 7.2*.

Factors within the animal and within the diet and/or environment may influence the extent to which the active compound is available to the animal at active metabolic sites. Reverting to the example of vitamin E it can be seen that a number of factors within the body system may act as modifiers of requirement. Tocopherols are fat soluble, and consequently short-term dietary inadequacies or metabolic demands may be accommodated from stored reserves. Selenium status may increase demand or act to 'spare' tocopherol (Agricultural Research Council, 1981). Similarly the level of absorbed polyunsaturated fatty acids (linoleic, linolenic and arachidonic acids) will influence the extent to which the active compound is available for other metabolic functions (Dam, 1962; Weiser and Salkeld, 1977). In this context studies reviewed by Wieser and Salkeld (1977) suggest that the requirement for D-α-tocopherol should be increased by

1.5 mg/g linoleic acid in the diet. A lower figure of 0.25 mg D-α-tocopherol/g PUFA was preferred by the Agricultural Research Council on the basis of trials in the rat. However, this value was based on an assumed ratio of linoleic and linolenic acid, and also assumed some biological contribution from γ-tocopherol. If the findings of McMurray and Rice (1982) that only α-tocopherol is absorbed by the pig are confirmed the higher figure of 1.5 may be more appropriate in the case of the pig.

The other considerations in the derivation of an allowance relate to the exogenous supply. In the case of the fat soluble vitamins the exogenous supply is primarily limited to the diet although, as will be discussed later, supplies of other vitamins may be available to the animal from coprophagy and from rooting.

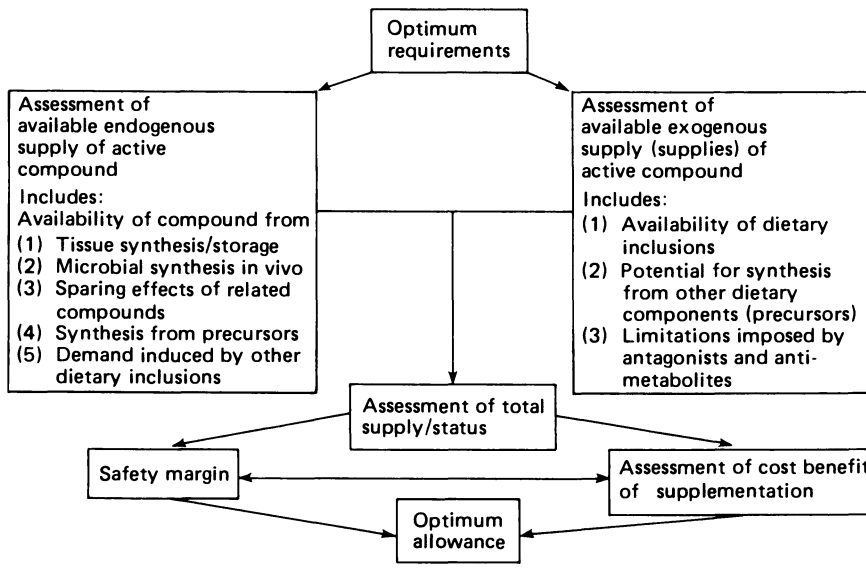

Figure 7.2 Schematic representation of stages in the derivation of an optimum vitamin allowance

Returning to the example of vitamin E, it becomes apparent from the work of McMurray and Rice (1982) that the estimation of dietary supply can be limited to the quantification of D-α-tocopherol. Because α-tocopherol fulfils an antioxidant function both *in vivo* and *in vitro* the α-tocopherol supply in a compounded diet may not be equal to the sum of contents of the individual components. This is particularly the case where fats and oils are added to the diet even if these are protected by synthetic antioxidants. Further losses of active compound can occur as a result of degradation and interaction with other dietary components during processing and storage (Kläui, 1976). At present the interrelationship between vitamins and mycotoxins is little understood. However, mycotoxins produce a 'stress' condition in animals and this too will imply an increased demand for vitamins (Scott, 1978).

Vitamin requirements of breeding female pigs

From the foregoing discussion it is apparent that an effective estimate of requirement demands a detailed knowledge of vitamin function and of supply status. In the case of the breeding female this information is frequently unavailable. The published literature pertaining to the vitamin requirements of the breeding pig has been reviewed recently by an Agricultural Research Council Working Party (1981). Their estimates of requirement are compared with two other estimates in *Table 7.5*.

Table 7.5 SUGGESTED REQUIREMENT OF VITAMINS (kg/DM)

	ARC (1981)	*NRC (1979)*[b]		*Zintzen (1975)*[d]
	Breeding sows and gilts	*Bred gilts and sows*	*Lactating gilts and sows*	*Breeding sows*
Fat soluble vitamins				
Retinol (mg/kg) or	0.7	1.3	0.7	3.3–6.6
β-carotene (mg/kg)	8.4	17.8	8.9	
Cholecalciferol or Ergocalciferol	—[a]	5.5	5.5	25–50
D-α-tocopherol (mg/kg) or	6.0	7.5	7.5	20–40
D-α-tocopheryl acetate (mg/kg)	10.2	11.1	11.1	
Phylloquinone (as menaphthone salts)	—[a]	2.2	2.2	2–5
Water soluble vitamins				
Thiamin	—[a]	1.1	1.1	2–3
Riboflavin (mg/kg)	3.0	3.3	3.3	4–6
Pantothenic acid (mg/kg)	10.0	13.3	13.3	10–20
Nicotinic acid (mg/kg)	—[a]	10.1[c]	10.1[c]	15–25
Pyridoxine (mg/kg)	1.5	1.1	1.1	3–5
Cyanocobalamin (μg/kg)	15.0	16.7	16.7	20–40
Folic acid (mg/kg)	—[a]	6.7	6.7	—
Biotin (μg/kg)	—[a]	111	111	150–200
Ascorbic acid	—[a]	—	—	—
Choline (mg/kg)	1000–1900	1389	1389	800–1000

[a]No data available to use as a basis for estimate of requirement.
[b]Requirements reflect the estimated levels of each nutrient needed for optimal performance when a fortified grain–soyabean meal diet is fed.
[c]High nicotinic acid requirements reflects low availability of nicotinic acid in maize and maize products.
[d]German Study Group for Micronutrients in Animal Nutrition (1972) cited by Zintzen (1975).

It is a measure of the limited research on the vitamin requirements of the breeding pig that they considered that there was inadequate reliable data on which to base any estimate of requirement for seven of the vitamins (choleocalciferol, phylloquinone, thiamin, nicotinic acid, folic acid, biotin and ascorbic acid). For one other (riboflavin) the estimate was based on a single trial. In the case of those water soluble vitamins for which an estimate was offered, the range of values in the literature was so great

Table 7.6 SOME REPORTED EFFECTS OF A SUBOPTIMAL PROVISION OF WATER SOLUBLE VITAMINS IN REPRODUCING FEMALE PIGS

Thiamin	Loss of appetite (inconsistent)	
	Premature parturition (9–11 days)	
	High perinatal mortality	
	Weak leg condition in piglets at birth	
	Reduced weaning weight	Ensminger, Bowland and Cunha (1947)
Riboflavin	Erratic and lost appetite	
	Poor maternal weight gain	
	Premature parturition (4–16 days)	
	Death and resorption of fetuses	
	Enlarged front legs in piglets	
	Generalized oedema of piglets	
	Hairlessness of piglets	Ensminger, Bowland and Cunha (1947)
	Poor conception rate and reproduction	
	Poor reproduction and lactation performance	Miller *et al.* (1953)
	Anoestrus in gilts	Esch, Easter and Bahr (1981)
	Reduced antibody production	Harmon *et al.* (1963)
Pantothenic acid	Inappetance	
	Reduced water intake	
	'Goose stepping'	
	Diarrhoea and rectal haemorrhages	
	Failure to carry pregnancy to term	Ensminger, Colby and Cunha (1951)
	Locomotor disturbances in piglets	Teague, Grifo and Palmer (1971)
	Atrophy of sexual organs—anoestrus	Ullrey *et al.* (1955)
	Reduced litter size at birth and weaning	
	High proportion of still births	Davey and Stevenson (1963)
	Deficiency symptoms in surviving piglets	Goodwin (1962)
	Reduced antibody production	Harmon *et al.* (1963)
Nicotinic acid	No reported effects of deficient diets	
Pyridoxine	Reduced litter size	Ritchie *et al.* (1960)
		Wöhlbier and Siegal (1967)
	Reduced growth rate in piglets	Miller *et al.* (1957)
	Reduced antibody production	Harmon *et al.* (1963)

Cyanocobalamin	Reduced conception rate	Frederick (1965)
	Reduced numbers born	Frederick and Brisson (1961)
	Reduced birth weight	Teague and Grifo (1966)
	Increased incidence of stillbirths	Teague and Grifo (1964)
Folacin	Reduced reproductive performance	Ensminger, Colby and Cunha (1951)
Biotin	Reduced litter size	Brooks, Smith and Irwin (1977)
		Halama (1979)
		Easter *et al.* (1979)
		Pederson and Udesen (1980)
		Brooks and Simmins (1980)
		Michel and Mastachi (1981)
		Penny *et al.* (1981)
		Robres Serrano and Garcia de la Calera (1981)
	Increased weaning to remating intervals	Brooks, Smith and Irwin (1977)
	Reduced conception rate	Simmins and Brooks (1982)
		Bryant *et al.* (1981)
		Pederson and Udesen (1980)
	Reduced piglet gains	Brooks, Smith and Irwin (1977)
		Simmins and Brooks (1982)
	Increased incidence of hoof lesions	Triebel and Lobsiger (1979)
		Penny *et al.* (1980)
		Brooks and Simmins (1980)
		Bryant *et al.* (1981)
		Halama (1979)
		Grandhi and Strain (1980)
		Money and Laughton (1980)
		Glättli (1975)
		Pederson and Udesen (1980)
Ascorbic acid	Reduced incidence of naval bleeding	Sandholm, Honkanen-Buzalski and Suomi (1981)
	Reduced piglet mortality	Corbett *et al.* (1980)
Choline	Rough coated splay legged piglets	
	Poor piglet gains	Ensminger, Bowland and Cunha (1947)
	Reduced litter size	Kornegay (1971)
		Kornegay and Meacham (1973)
		NCR-42 (1976)
	Reduced conception and farrowing rate	Stockland and Blaylock (1974)

(varying by as much as 1000%) that any estimate must be viewed with considerable caution.

An examination of the literature from which the conclusions were drawn gives further cause for concern. The majority of the trials were conducted in the USA using breeds, management systems and basal diets which have little in common with those used in western Europe. Moreover, many trials were conducted 20 or more years ago with genetically unimproved animals of very low productivity by current standards.

The trials reported fall into two main categories. The first category are those trials in which researchers have attempted to create deficiency conditions by the use of unusual dietary formulations and then added the vitamin being studied in order to assess the level of inclusion at which overt clinical deficiency symptoms disappear. Such trials have severe limitations. In the case of the fat soluble vitamins the depletion period may be extremely long and will depend upon the extent of initial body stores. In the case of vitamin C and vitamin D the animal's capacity for tissue synthesis makes total depletion impossible. In the case of the B-group vitamins there may be a contribution from intestinal synthesis (*see later*) and the extent of this synthesis may be influenced by other dietary factors. In the absence of reliable biochemical indicators it is not possible to ascertain whether or not a deficient state has been achieved before repletion is attempted.

The second group are those trials in which vitamin additions have been made to 'conventional' diets and specific parameters recorded to assess the presence or absence of a 'response'. The variation in results from such trials can be confusing but should not be unexpected. The principal problem in interpreting such trials is in assessing the contribution of available vitamin active compound from the basal diet.

The remainder of this chapter will concentrate on the water soluble vitamins and in particular those comprising the B-group complex. For a discussion of the contribution of the fat soluble vitamins to sow reproduction the reader is referred to the Agricultural Research Council (1981) review.

Although the published literature is often fragmentary and/or conflicting it does demonstrate that a number of commercially significant aspects of sow productivity are influenced by the level of vitamin provided in the diet. Some effects of an inadequate supply of water soluble vitamins on the performance of the breeding pig are summarized in *Table 7.6*. For the reasons indicated previously it is inappropriate to indicate levels above and below which responses have been obtained.

Vitamin responses in breeding pigs

A vitamin allowance would normally be derived from an assessment of requirement to which an appropriate safety margin would be added to allow for

(1) anticipated and potential losses of active compound, and
(2) biological variation within the target population.

Such a safety margin (or insurance addition) can only be added with confidence if the estimate of requirement is considered appropriate. As mentioned previously many of the existing estimates relate to animals and management systems which are not representative of those found in the UK. Consequently, it is necessary to consider the effect that such differences may have on requirement and make suitable adjustments to the estimate of requirement before adding on the safety margin. A number of factors which are likely to indicate an increase in vitamin allowance are listed in *Table 7.7*. It is not possible to produce meaningful estimates of the

Table 7.7 FACTORS LIKELY TO INDICATE AN INCREASE IN VITAMIN ALLOWANCE

A *Animal factors*	
(1) Selection for increased growth rate and/or reduced feed/unit gain	Change in relationship between 'maintenance' and 'production' requirement and between requirements for deposition of different tissues.
(2) Increased productivity of breeding stock	Increased use of cross-breeding and reduced lactation length therefore changed relationship between feed input and biological output.
(3) Use of different genotypes (breeds?)	Genetic differences in requirements and/or ability to meet requirement from endogenous production.
(4) Health status	Increased disease challenge resulting from larger unit size and increased stocking density.
B *Management factors*	
(1) Total confinement—reduced natural illumination	Reduction in natural illumination/total illumination. Increased requirement for vitamin D?
(2) Total confinement—reduction of exogenous sources of vitamins	Adoption of stalls/slatted floors reduces opportunities for rooting and/or coprophagy (potential source of B vitamins).
(3) Increased stocking density	Increased disease challenge, increase in 'stress' due to behavioural dysfunctions.
C *Nutritional factors*	
(1) More closely specified diets	Less nutritional surpluses (i.e. raw materials) which might contribute to vitamin supply.
(2) Formulation/raw material changes	Use of raw materials in which vitamins may be less well supplied and/or supplied in unavailable forms.
(3) Supply in relation to changed productivity	Need to adjust allowances of vitamin in relation to productivity changes (may not be linear) and need to consider vitamins previously considered adequately provided by raw materials.
D *Antinutritional factors*	
(1) Adverse effects of processing/storage	Need to accommodate unavoidable losses in processing and storage and effects on availability arising from interactions between dietary components.
(2) Mycotoxins/antimetabolites/antagonists	
(3) Increased drug use	Relates to health status but some drugs have antivitamin action thereby increasing requirements.

extent to which such factors will increase the need for vitamin fortification. Indeed the influence of the factors is likely to vary greatly for different vitamins.

It is possible to illustrate some of the points made in *Table 7.7* by reference to the recent studies on biotin response in sows. Until a few years ago it was generally assumed that the pig's requirement for biotin could be met without recourse to biotin supplementation of diets. The pig's biotin supply was considered to come from three sources:

(1) biotin present in natural dietary components,
(2) biotin elaborated by the intestinal microflora,
(3) biotin ingested in faeces (coprophagy).

Each of these possibilities make certain assumptions which are not supported by the evidence now available. As these assumptions could be of significance in the case of other B-group vitamins they are worthy of some consideration.

DIETARY SUPPLY OF BIOTIN

Largely as a result of studies in poultry it has been necessary to reappraise the potential supply of biotin from dietary raw materials. Estimates of the biotin content of raw materials were traditionally based on microbiological assays. However, such assays proved misleading as chick bioassay established that the biological availability of the biotin in raw materials could vary from 0–100% (Anderson and Warnick, 1970; Frigg, 1976). Consequently, changes in diet formulation which take no account of the available biotin content of the raw materials included could have significant effects upon supply. Calculations based on UK survey data suggested that between 1967 and 1976 the provision of biotin per weaner reared to eight weeks of age fell by about 27% (Brooks, 1978). During the same period the need to increase the supplementation levels had been recognized and as a consequence vitamin A supply had been increased by 140% and the supply of vitamin D by 59% (*Figure 7.3*). The reduction in biotin supply was in part due to an altered pattern of raw material usage (Putnam, 1977) and partly to an increase in sow productivity which resulted in a reduction in feed intake per weaner reared to eight weeks of age of approximately 22% (*Figure 7.4*). Notwithstanding any difference that changes in raw material usage may have had, a similar change in provision will have occurred in the case of other B-group vitamins unless corrected by vitamin supplementation.

The problem of biological availability of an active form of a vitamin in raw materials is of considerable significance particularly so in the case of those vitamins which are not normally included as part of a standard vitamin supplement. In this context folic acid and nicotinic acid in particular deserve further attention, as it has been established that the naturally occurring forms of these vitamins differ considerably in their distribution in animal feeds and in their bioavailability (Belcic and Friesecke, 1979; Luce, Peo and Hudman, 1966, 1967).

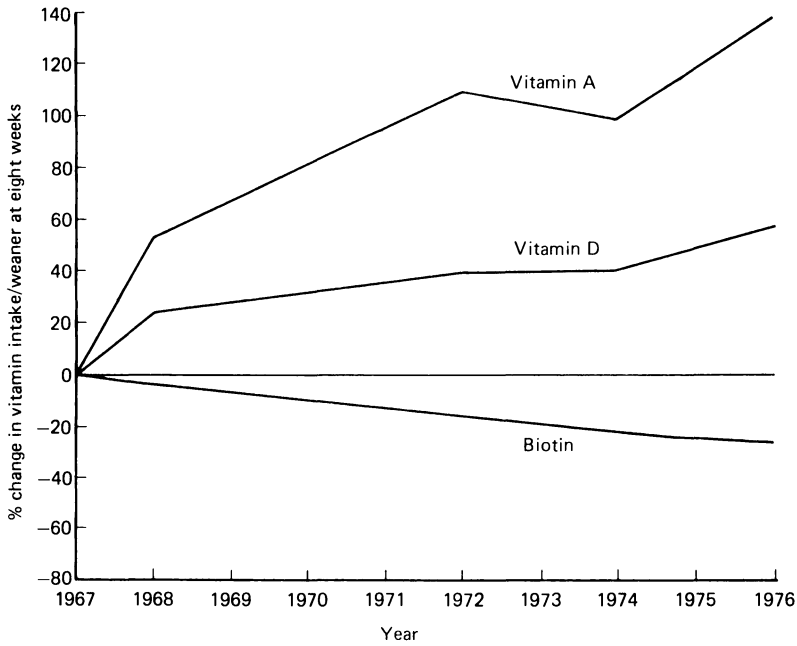

Figure 7.3 Change in intake of vitamins A, D and biotin by sows per weaner reared to eight weeks expressed as a percentage of 1967 value

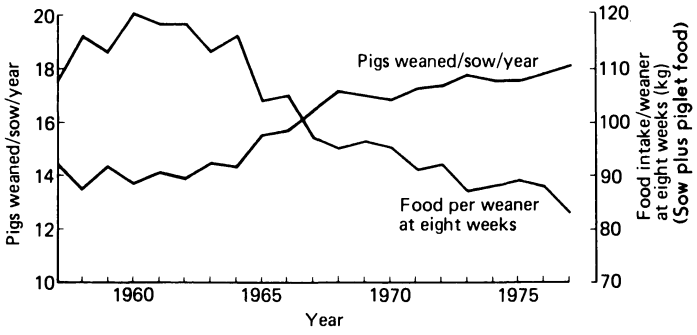

Figure 7.4 Change in sow productivity and food consumption per weaner reared to eight weeks of age (1957–1977)

INTESTINAL SYNTHESIS OF BIOTIN

In common with the other B-group vitamins biotin is synthesized by micro-organisms in the intestine. Indeed it is possible to demonstrate that net faecal outputs of biotin can exceed dietary inputs. What is less certain is the extent to which this microbial synthesis contributes to the animal's requirements. From the early studies in which biotin deficiencies were induced by the administration of sulpha drugs (Lindley and Cunha, 1946) it was assumed that these drugs destroyed the microbial population responsible for the production of biotin thus reducing the supply available to the

pig. However, Drochner and Völker (1979) injected labelled biotin into the caecum of pigs and found that only a minute fraction was absorbed and excreted in the urine, whereas the major part was found in the faeces. Much more information is needed on the contribution that microbial synthesis makes to the supply of the pig. While it is assumed that the vitamins produced in the hind gut of the animal are absorbed, experimental proof for direct absorption has been demonstrated only for vitamin B_{12} and vitamin K (Christensen, 1980).

CONTRIBUTION OF COPROPHAGY

It is possible that if intestinal synthesis is of benefit to the pig it comes about largely as a result of ingestion of faecal material. However, such an assumption cannot be validated from experimental evidence. On the contrary biotin responsive conditions have been demonstrated in sows which were housed in straw yards with ample opportunity for coprophagy (Brooks, Smith and Irwin, 1977). More recently it has proved possible to induce deficiencies in growing pigs sharing solid floored accommodation with pen mates receiving very high dietary inclusions of biotin (P.H. Simmins and P.H. Brooks, unpublished data). In the case of the chicken Whitehead and Bannister (1980) have shown that the contribution of biotin of faecal origin to the intake of broilers was only equivalent to 0.01 mg biotin/kg diet.

From these findings it would appear that intestinal synthesis and coprophagy make a minimal contribution to the biotin supply of the pig. Consequently, the dietary component assumes much greater significance. There is a need to determine whether this is also the case for the other B-group vitamins, for if they too make little contribution to the animal's supply current recommendations may require significant amendment.

The response of the breeding female to additional biotin

The information above demonstrates that classic thinking on the extent and nature of biotin supply to the pig was inaccurate and that the animal's supply had been reduced as a result of changes in management practice and sow productivity. However, these findings would have been of little significance had it not also been demonstrated that the change in supply had had an effect on commercial performance. Interest in biotin was reawakened by the study of Brooks, Smith and Irwin (1977). In that study a suspected spontaneous deficiency of biotin had resulted in a high incidence of foot lesions which was reduced by biotin supplementation. An unexpected benefit of supplementation was an improvement in reproductive performance. It would not have been surprising if the study had been dismissed as a rare abberation unlikely to be encountered again. However, foot problems and indifferent reproductive performance among sows are sufficiently widespread that a number of other researchers initiated trials to investigate the matter further. The results of these trials (reviewed by Brooks, 1982) conducted in a number of different countries with sows of

different genotypes, fed widely differing diets and in varied systems of management have generally demonstrated responses to an increased dietary supply of biotin. The nature of these responses is summarized briefly below.

RESOLUTION OF AND REDUCTION IN DEVELOPMENT OF HOOF LESIONS

Where hoof lesions already exist the best resolution has been obtained with dietary supplements of 2000–3000 μg/biotin/kg feed (Glättli, 1975; Hardy, 1978 personal communication; Comben, 1978; Pederson and Udesen, 1980). However, lesions resulting from an undersupply of biotin are very similar to lesions having an alternative aetiology. Consequently, no resolution was obtained if biotin insufficiency was not involved in the initial development of lesions. Furthermore, the opportunities for resolution have a marked effect upon response. Pigs housed on badly designed floors have little opportunity for recovery as traumatic injury exceeds the capacity of the hoof for regrowth and repair.

Lower levels of supplementation (200–500 μg biotin/kg feed) have also produced reductions in the number and/or severity of hoof lesions (Brooks, Smith and Irwin, 1977; Halama, 1979; Grandhi and Strain, 1980; Money and Laughton, 1980) but the time taken for resolution has been longer and the extent of the improvement less dramatic than when higher levels have been used.

Lower levels of supplementation (200–500 μg biotin/kg feed) have been found to exert a protective function when fed to clinically healthy gilts (Triebel and Lobsiger, 1979; Penny *et al.*, 1980; Brooks and Simmins, 1980; Bryant *et al.*, 1981). Gilts supplemented with such levels of biotin have developed fewer and less severe hoof lesions than unsupplemented controls.

INCREASES IN LITTER SIZE

Improvements in litter size have been demonstrated in a number of trials. Generalizations are difficult because the basal diets used in the trials reported have had available biotin contents ranging from 29–155 μg/kg and supplementation levels ranging from 100–2000 μg biotin/kg. Nevertheless, improvements in litter size ranging from 4 to 14% have been reported (Halama, 1979; Easter *et al.*, 1979; Pederson and Udesen, 1980; Brooks and Simmins, 1980; Michel and Mastachi, 1981; Penny *et al.*, 1981; Robres Serrano and Garcia de la Calera, 1981). Unfortunately, in only one trial, that of Michel and Mastachi (1981), was more than one level of supplementation used. In that trial increasing the dietary supply from 175 to 275 μg available biotin/kg diet produced a significant improvement in litter size suggesting that a level of 175 μg available biotin/kg diet is insufficient to support optimum reproductive performance.

REDUCED WEANING TO CONCEPTION INTERVALS

Improvements in weaning to remating interval of 13, 18 and 24% have been reported in three recent trials (Bryant *et al.*, 1981; Pederson and Udesen, 1980; Brooks and Simmins, 1980). In a recent long-term trial (Simmins and Brooks, 1982) it was found that the weaning to remating

Table 7.8 EFFECT OF BIOTIN SUPPLEMENTATION ON POST WEANING PERFORMANCE OF SOWS[a]

	Control[b]	*Supplemented* (+350 µg biotin/kg)	*SED*
Interval from weaning to oestrus (days)	11.9	9.0	1.7
% sows returning to oestrus within ten days of weaning	74.6	83.2	—
interval from weaning to conception (days)	16.5	10.4	1.4[f]
% sows conceiving within ten days of weaning	71.8	80.6	—
% sows treated for anoestrus[c]	17.0	7.3	—
% sows conceiving at first service[d]	95.2[e]	100.0[e]	—

(After Simmins and Brooks, 1982)
[a]Average for first four parities.
[b]Control diet contained 32 µg available biotin/day.
[c]Sows not returning to oestrus within 29 days of weaning were treated with PG 600.
[d]Sows returning to service within 29 days of weaning.
[e]Includes returns to service at first post-pubertal oestrus.
[f]Significant at $P<0.05$.

interval and conception rate of sows was significantly improved when a diet containing 32 µg available biotin/kg was supplemented with 350 µg biotin/kg. (At a post-weaning feed level of 3.5 kg/sow/day this represented a daily intake of approximately 1350 µg available biotin per day) (*Table 7.8*).

Selection of parameters for measurement of a vitamin response

An examination of the various trials reported above raises important questions about the selection of parameters for measurement of a reproductive response in sows. Researchers tend to work with selected populations of animals and to concentrate on specific parameters such as litter size, piglet birth weight, piglets weaned and weaning weight. However commercial producers usually measure productivity of large populations of animals, of varying parity, on the basis of annual productivity. Thus small variations in factors such as longevity, conception rate and weight of pigs weaned per litter are of great significance to the commercial producer. It is not always possible to calculate values for annual productivity from research data due to the absence of certain items of information. In the recent Seale-Hayne trial the data were collected in such a way that it was possible to calculate annual productivity results for control and supplemented animals. It was interesting to find that although a number of individual parameters of sow performance failed to differ significantly, when sow output was expressed in terms of kg of weaner produced per sow

Table 7.9 EFFECT OF BIOTIN SUPPLEMENTATION ON ANNUAL SOW PRODUCTIVITY[a]

	Control[b]	*Supplemented* (+350 μg biotin/kg)	*SED*
Pigs born/sow/year	23.08	24.05	1.45
Pigs weaned/sow/year	18.58	20.00	1.02
Wt of pigs born/sow/year (kg)	31.52	34.14	1.70
Wt of pigs weaned/sow/year (kg)	153.64	170.97	7.42[c]

[a]Calculated from herd entry at 170 days of age to weaning of fourth litter for sows completing four parities only.
[b]Control diet contained 32 μg available biotin/day.
[c]Significant at $P<0.05$

per year there was a significant response to biotin supplementation (*Table 7.9*).

In order to obtain estimates of response which are actionable by the nutritionist there would be a strong argument for expressing responses in terms of the product which the producer ultimately sells, i.e. a given number and weight of pigs per sow per year. Expressing results in this form would also make the assessment of potential cost benefit much simpler.

Ideally in reporting biological responses a correlated response in an accepted biochemical indicator should be included to allow comparison between trials. Unfortunately for many of the vitamins no reliable biochemical indicator is available. The development of such indicators would be of great value not only in experiments, but also in monitoring provision in the field.

Possibility of responses to other vitamins

Some aspects of the recent research on biotin have been discussed in some detail as the findings may have relevance to other of the B-group vitamins. With the exception of the recent study of riboflavin involvement in oestrus cyclicity in gilts (Esch, Easter and Bahr, 1981) there has been little work on B-group vitamins in breeding females in the last 20 years. There would appear to be justification for a reappraisal of their role in sow nutrition in the 1980s. In addition to possible effects on litter size and breeding regularity three other areas would appear worthy of further attention.

(1) the role of vitamins in immune response,
(2) the role of vitamins in fat metabolism in the breeding female,
(3) the influence of vitamin levels in milk and colostrum on piglet viability.

VITAMINS AND IMMUNE RESPONSES

The involvement of vitamin E in immune responses has already been mentioned. Other vitamins which have been demonstrated to have an involvement in immune responses are retinol, pyridoxine, folic acid, choline, ascorbic acid, riboflavin and pantothenic acid (Christensen, 1980;

Harmon *et al.*, 1963). Modern methods of production often increase the potential disease challenge. In order to overcome this producers increasingly rely upon vaccination programmes (e.g. anti-K 88 *E. coli* vaccines) and the deliberate infection of stock at non-critical times (e.g. with transmissible gastroenteritis) in order to obtain or maintain disease resistance. Any vitamin supported improvement in immunoglobulin production would benefit the sow. More particularly it could improve the disease resistance of her offspring who are totally dependent upon the acquisition of immunoglobulins from the sow's colostrum for their resistance to disease in the immediate post-natal period.

VITAMINS AND FAT METABOLISM

Fat metabolism is of considerable concern to sow nutritionists. Fats and oils are being used to a greater extent to increase energy supply to the piglet in late pregnancy and early lactation. The variable responses obtained in trials where additional lipid has been fed in late pregnancy and early lactation may in part be explained by differing levels of vitamin provision. Retinol, D-α-tocopherol, riboflavin, niacin, pyridoxine, pantothenic acid, biotin and choline are all involved in fat metabolism. In many cases their contribution to intermediary metabolism, through rate limiting enzyme systems, could affect the utilization of dietary fat and the extent of deposition and catabolism of body fat stores. With the exception of D-α tocopherol, which is usually added to fat diets at higher levels for its antioxidant properties, the supply of vitamins involved in fat metabolism has often remained unaltered when fat additions have been made to the diet of the sow. It is not impossible that nutritionists will soon have to adopt the concept of 'first limiting vitamins' in the same way that they have adopted the concept of 'limiting' amino acids.

Table 7.10 EFFECT OF BIOTIN SUPPLEMENTATION ON MONOENE SATURATE RATIO OF SOWS' MILK[a]

	Phospholipid fraction		*Neutral lipid fraction*	
	Control	*Supplemented*	*Control*	*Supplemented*
Early lactation	0.78	0.81	1.18	1.27
Late lactation	0.94	1.04	1.21	1.45

(P.H. Simmins and P.H. Brooks, unpublished data)

[a]Monoene saturate ratio = $\frac{C16.1 + C18.1}{C16.0 + C18.0}$

A pilot study at Seale-Hayne College has shown that the biotin status of the sow may affect the composition of sow depot fat and the fatty acid composition of sows' milk (*Table 7.10*). The newborn pig utilizes milk fat as an energy source and it has been shown that the rate at which the newborn pig oxidizes individual fatty acids varies considerably (Boyd *et al.*, 1981). Consequently, changes in both quantity and composition of milk fat may be of significance to the newborn pig.

The vitamin status of the sow may also have an effect upon the quantity, composition and lability of sow depot fat. It has been demonstrated that in

Table 7.11 EFFECT OF DIETARY BIOTIN ON MONOENE SATURATE RATIO OF DEPOT FAT IN GROWING PIGS[a,b]

Authors	*Biotin level in diet* (μg/kg)	*Monoene saturate ratio*
Bühlmann (1973)	'Deficient'	2.12
	'Control'	1.09
Streiff and Völker (1978 personal communication)	0	2.32
	100	0.95
	300	0.96
Streiff, Frigg and Völker (1978, personal communication)	0	2.29
	300	1.56
	900	1.45
	2700	1.31
Völker and Streiff (1978 personal communication)	0	2.22
	40	1.31
	100	1.26
Simmins and Brooks (1981 unpublished data)	0	1.60
	40	0.78
	120	0.76
	720	0.74

[a]Monoene saturate ratio = $\frac{C16.1 + C18.1}{C16.0 + C18.0}$

[b]Samples were subcutaneous fat except the trial of Simmins and Brooks (1981) which used perinephric fat.

the growing pig the dietary biotin supply has a marked effect on the fatty acid composition of depot fat (*Table 7.11*). This is of some significance in the growing pig where fatty acid composition of depot fat has an effect on fat hardness and its 'quality' in manufacture. The relevance of such changes in the depot fat of sows await investigation.

VITAMIN LEVELS IN MILK

The levels of vitamins present in milk are influenced by the maternal supply. Until it starts to consume solid food the piglet is dependent upon the limited stores of fat soluble vitamins deposited *in utero* and the vitamins obtained in colostrum and milk. As the water soluble vitamins are not stored to any significant extent, or for any appreciable time, the supply of these vitamins in the milk is of particular importance to the neonate. In the newborn pig exogenous glucose intake is not sufficient to cover total glucose utilization (Pegorier *et al.*, 1981). Consequently the piglet has to rely upon glycogenolysis and gluconeogenesis in order to maintain glucose homeostasis. The findings of Pegorier *et al.* (1982) that the rate of gluconeogenesis is two- to threefold higher in suckling than in non-suckling pigs is of great significance. Although Pegorier *et al.* (1982) make no suggestions as to why this should be, it could well be that suckling provides a source of vitamins essential for the efficient operation of the gluconeogenic pathway. Clearly there is a need to examine more closely the metabolism of the piglet and to evaluate the part which vitamins acquired in the milk play on the operation of metabolic pathways in the newborn animal.

Conclusions

The chapter has concentrated particularly upon the water soluble vitamins because

(1) there is little information about the extent or availability of vitamins from intestinal synthesis,
(2) modern systems of husbandry reduce the opportunities for coprophagy,
(3) there is virtually no *in vivo* storage of water soluble vitamins,
(4) such estimates of requirement as exist may be inappropriate to the highly productive sows used today.

It is concluded that changes in productivity and sow management may have increased the requirement of these vitamins significantly. Furthermore, the involvement of the water soluble vitamins in fat metabolism and immune response is only poorly understood. It is to be hoped that the interest generated by recent experience with biotin will encourage nutritionists to undertake a thorough reappraisal of the requirements and allowances of other vitamins.

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8

SYSTEMS OF CALF REARING

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Calf feeding systems have moved from the simple towards the highly sophisticated. It is therefore pertinent to ask why such a movement should have taken place. Can it be the loss of the dairymaid; is it the response to so many men moving out of agriculture or is it perhaps that some of the systems actually produce better reared calves? The calf, like the cow, is having its feeding system mechanized for some of the same reasons, mainly perhaps to remove labour by automation, but also to produce a more homogeneous feeding pattern and remove many of the small inconsistencies inherent in the job when done by hand. The trend appears to be leading back to *ad-libitum* feeding which we have spent nearly two decades escaping from.

Back in 1966 workers at the Grassland Research Institute (Taylor, 1966) were feeding calves in straw bale hutches at grass on *ad-libitum* cold milk replacers. The system never caught on, partly because outdoor feeding has little appeal in the British climate but also because there was no way of preserving the milk in a feedable condition in the containers then in use. A daily mixing on a wet hillside held few attractions for stockmen. An imported machine from the USA overcame some of the objections to *ad-libitum* feeding by producing a warm feed. Expense held back the spread of machine feeding although there were a good many machines in use in some parts of the country.

In spite of the Roy dictum, that calf health and wellbeing deteriorate the further the animal is moved from suckling, systems were evolved to feed once-a-day instead of twice, and then to feed cold instead of warm milk replacer. The single feed, mixed with water direct from the cold tap, without heating, had and still has considerable attraction. In competent hands once-a-day cold feeding can and does produce healthy calves. Such a routine allows the stockman considerable flexibility in choice of time of feeding which can be fitted, where convenient, into a working day.

There are naturally penalties to be paid for convenience. Cold feeding does not always give as good results as warm, particularly during long spells of severe weather. Daily liveweight gains can be very small and some calves may end up at weaning weighing little more than at birth. However,

if general management is good, bedding, ventilation and drainage are all adequate, small liveweight gains may matter little if the animals are healthy and this may largely be a matter of good, early supplies of colostrum and a vigilant eye from the stockman.

After the reduction in labour input in calf husbandry, attention began to be paid to reducing costs, mainly those associated with the early milk feeding period. Cold feeding once-a-day became cold colostrum feeding. In the early days colostrum was stored, deep frozen, in polythene bags. No farm technique obviously, but it was noticed that colostrum, when kept unfrozen, fermented rapidly and then had a storage life, like any other fermented product, which made it feasible to store and use it over long periods of time. Feeding was simple, 3 ℓ once-a-day plus 1 ℓ of warm water if the weather was exceptionally cold (Swannack, 1971).

The collection of adequate colostrum is not always easy, the temptation to run it into the bulk tank is strong, both because it adds to the total salable volume and because it is often difficult to extract it from milking systems, particularly those which have low level jars. The 'gash' line, now fitted as an optional extra, should be a must in all systems to allow easy collection not only of colostrum but also of unsalable milk containing antibiotic residues. *Table 8.1* indicates the proportion of dairy farmers actually withholding colostrum from the bulk tank.

Table 8.1 PROPORTIONS OF FARMERS WITHHOLDING MILK FOLLOWING CALVING (FOUR DAYS)

	% withholding milk for four days
Always	58
Sometimes	14
Never	28

Source: MMB survey

The average quantity of colostrum collected over the first four days after calving is about 40 ℓ. This quantity cannot hope to feed all calves born but it usually suffices for replacement heifer calves, after the early disposal of the bull calves. Abrupt changes of food, to either whole milk or milk replacer, when colostrum quantities are small or run out, were shown not to upset the calves (Swannack, 1972). This system of calf feeding has been adopted widely in the USA, Australia and New Zealand although the British farmer has been slower to adopt it.

Traditionally calf husbandry has encouraged the keeping of the calf on a fluid diet up to about 12 weeks of age. Anyone who has reared a good few calves will know that the animals, once over the fluid phase of feeding, seldom run into much scouring problem. It would seem sensible to exploit this observation by earlier weaning, turning the young calf rapidly into a multi-gastrate. Friesian heifer calves wean at very early ages on a restricted milk diet and the provision of a palatable calf starter concentrate, in the right physical form, helps early consumption and promotes the function of the rumen. Many calves have been weaned abruptly at 21 days and below, when eating 500–700 g/day of a starter. Floyd Ewin (1977) showed that in the Friesian heifer calf satisfactory solid food intake tends to equate with 28 days of age. Early weaning, on restricted diets, is here to stay. It is a

convenience and needless to say milk replacer diets are at least three times more expensive than concentrate starter feeds.

The biggest change in calf feeding systems for nearly a generation took place almost explosively in the late 1970s. This revolution altered both feed and feeding practice. Acid milk arrived and with it the return to *ad-libitum* cold feeding that had foundered on the slopes of the Thames Valley a decade before. The milk that had soured and become unfeedable then could now be protected from bacterial spoilage for about three days by the simple addition of an acid to the powder so that when mixed with water a product of a pH of about 5.6 resulted.

The acid milk replacers as a group grew from the import of a Dutch product, based largely on whey powder, partially demineralized and de-lactosed, and made from a sweet Gouda whey, to which was added an organic acid at about the 1% level. Acid milk powders proliferated; some of the zero based types, almost wholly whey powder based, were acidified to a much lower pH (4.2) than was possible with casein containing types that were 60% plus dried skim milk.

The acid milk powders were designed to give the calf feeder a trouble free system and one that was cheap and easy to set up. There were claims that calf health was improved and that calves did not scour on the system by virtue of the acidity of the feed. Certainly the system, a container connected by a small bore tube to a teat, was cheap to install, but under good experimental conditions acidified milk could not be shown to have an effect on the incidence of scouring in calves (Stobo and Roy, 1980; Fallon and Harte, 1980). Field reports, however, continued to support these claims and Roy (1980) stated that 'possibly under more adverse conditions a beneficial effect might have been apparent'. Regardless of health claims, calf rearers took to the cold acid milk system and now that the food could be relied upon to keep in a condition in which it would flow through a teat the system could be adapted to feed individuals or groups of calves with a clean and fill up on only two days a week which, if one was a Friday, eliminated week-end work.

Ad-libitum cold feeding has its problems, some purely physical. Barrels are heavy when full and difficult to shift about. It is not always possible to use a length of hose and tip powder from a bag on your shoulder at the same time. Cold weather not only leads to reduced intake by the calf but also, when the temperature drops below zero, to no intake at all and to the necessity for restoring flow in a system frozen solid whose pipework is not metal and therefore cannot be coped with in the usual farm manner with a blowlamp, or wads of diesel soaked straw burning at exposed corners of pipe systems.

The problems associated with the calves themselves fall into two categories. One has to do with the social hierarchy, or 'pecking order', the other with the difficulties of restraining the natural gluttony of the animal. Heifer replacement calves on experiment at Bridgets EHF showed very uneven growth rates when batch reared. This was not a case of too many to a teat, nor necessarily a function of birth date, but it did have something to do with size in the group. There is scope for more trial work in this area. Restraining gluttony to prevent a check at or before weaning has not yet been mastered. In one trial at Bridgets EHF a comparison was made of

Table 8.2 TOTAL FEED INTAKE (kg) TO WEANING AT 35 DAYS USING DIFFERENT MILK OR MILK REPLACERS EITHER *AD-LIBITUM* OR RESTRICTED

	Whole milk	*Dried skim milk based*	*Dried whey powder based*
Milk or milk replacer intake			
Restricted	15.9	14.5	14.9
Ad-libitum	27.8	27.8	29.8
Weaning concentrates intake			
Restricted	8.4	11.3	9.0
Ad-libitum	4.4	5.3	5.1

total feed intake to 35 days of age when calves were given different milk or milk substitutes, and the data are presented in *Table 8.2*.

It is plain from these results that on a restricted 'milk' input two calves can be reared for the price of one on *ad-libitum* feeding.

An interesting observation arose during this trial. The calves given *ad-libitum* whole milk, self limited their intake at an average of 7 ℓ/day, where our experience with *ad-libitum* feeding of milk replacers has nearly always shown daily intakes of nearer 9 ℓ.

Differences in daily liveweight gain between calves on the restricted and *ad-libitum* milk intakes are shown in *Table 8.3*.

Table 8.3 DAILY LIVEWEIGHT GAIN (kg/DAY) TO WEANING AT 35 DAYS FOR CALVES FED MILK OR MILK REPLACERS *AD LIBITUM* OR RESTRICTED

	Whole milk	*Dried skim milk*	*Dried whey powder*
Restricted	0.46	0.47	0.40
Ad-libitum	0.50	0.48	0.59

It was probably inevitable that *ad-libitum* cold feeding should cause some problems and that winter rearing of calves should exacerbate these. In general, manufacturers of calf milk replacers for cold feeding *ad-libitum*, have set a sensible advisory standard, printed on the bag, suggesting that cold feeding systems should not be operated at below 10 °C.

Our experience with cold *ad-libitum* group feeding has suggested that on large farms, where batch calving is practised, such a system may work reasonably well in early autumn in careful hands. Wide disparities in age or size within a group can lead to poor 'doers', and for this reason restricted feeding in individual pens is preferred for rearing replacement heifers. For an all in all out beef calf rearing system it can work well.

There is perhaps a new dawn coming. The interest stimulated by acid milk and a cold *ad-libitum* feeding system, not to everyone's taste in hard winters, has led to a new wave of warm feeders. Bigger, better built, with more and more sophisticated controls are becoming available. This may well be the age of the warm milk dispenser now that the enthusiasm for cold acid milk feeding has declined somewhat.

The new interest in warm machine feeding stems probably from the concern in Europe over the welfare of the calf in the traditional systems of veal production in which calves were kept in individual pens of a somewhat restrictive nature, usually on slats and in semi-darkened houses where they

were prevented from ruminating because they were fed no roughage. The demand for the calf to be allowed to develop rumination led to the provision of some straw, usually as a cube, and finally to the development of machine feeding in straw yards. The calf came out from the dark and off the slatted floor onto straw. Twice daily bucket feeding was replaced by a feeding system producing a flow of warm milk on demand.

The future of veal production may be uncertain, but machine feeding of calves appears to be spreading rapidly amongst farmers. A recent count of machines on farms suggests that there are probably 4000 to 5000 in Britain and that early design faults have been rectified. Like all machinery, they require regular attention to give continuous service and perhaps also a 'Unipart' type replacement service. For whatever reason they are used, and for some users they appear to have been installed on a whim rather than a reasoned process, there is no doubt that they produce good calves, provided the animals are properly teat trained. They suffer from the same problems, only more so, as the cold *ad-libitum* feeding systems, and are even more difficult to wean calves away from. Calves drink even more milk when offered it warm, and solid intake is slow to develop when warm milk is 'on tap'. A system that works well for the *ad-libitum* fed veal producer is bound to be expensive when applied to the rearing of calves for either beef or dairy herd replacements. A recent small trial at Bridgets EHF, the data from which are shown in *Table 8.4*, illustrate this point.

Table 8.4 PERFORMANCE OF CALVES FED WARM MILK REPLACER *AD LIBITUM* BY MACHINE

	Charollais-X	*Limousin-X*
Birth wt (kg)	51.5	49.5
Wt at sale (kg)	124.0	85.5
Breakeven price including purchase cost (£)	182.5	127.3
Sale price (£)	182.2	154.0
Difference (£)	–0.30	+26.7
Age at sale (weeks)	9.5	6.0
Av. powder intake (kg)	59.4	

It is evident from these data that some restriction on food consumption is desirable. The machine used at Bridgets EHF can now be fitted with what can be called a 'rationer'. This gadget can be set to supply either milk replacer or warm water and the calf is alerted by a flashing light when the 'meal' is on tap. This should allow milk replacer consumption to be kept at a reasonable level without the usual disconnection techniques.

Although probably not yet of commercial application, the next stage has been reached in automating the *ad-libitum* feeding system. The whole machine can now be connected to a computer system and the calf, with its miniature transponder, can trigger off an individually programmed feed. This machine should be available for trials very shortly and there is no doubt that it could be an invaluable research tool allowing the treatment of the individual within the group.

One further question needing consideration is whether mastitic milk can be usefully employed in calf rearing systems. 'Tubing' the mastitic cow has been a common and accepted practice for many years. Whatever its merits

may be, it is simple to do compared with the practice of keeping the cow empty by multiple milking. As long as 'tubing' is the accepted practice in the industry the Milk Marketing Board (MMB), more and more of whose primary raw material is going into manufacture, will be obliged to place ever more swingeing penalties on farmers who do not withhold milk containing antibiotic residues. A recent survey shows the proportion of farmers withholding milk from antibiotic-treated cows (*Table 8.5*).

Table 8.5 PROPORTION OF FARMERS WITHHOLDING MILK FOLLOWING THERAPY FOR MASTITIS

	% withholding milk
Always	68
Sometimes	12
Never	20

The bottom one-third in this table may shortly find it expedient to fall into line with the top two-thirds.

The cost to the industry of this withheld milk has been variously estimated. The Central Veterinary Laboratory, working on mastitis control, at a recent Open Day estimated that 309 000 ℓ of milk are discarded daily by the industry. Multiply that up by the figure of 15 p/ℓ and the 365 days of the year and the figure becomes £17 million/annum loss to the industry.

MMB penalties are designed to keep this antibiotic contaminated milk at home on the farm. If kept at home, has it a use? Whether we approve or not, the answer a lot of farmers, worldwide, are giving is yes; it can be and is fed to calves. Kesler (1981), reviewing the literature, concluded that mastitic milk is a safe feed for calves if fermented to allow antibiotic residues to disappear (Keyes *et al.*, 1976, 1979, 1980). Otterby *et al.* (1980), Schaffer and McGuffey (1980), Windle *et al.* (1981), Keith *et al.* (1981), Loveland (1982) and Yndestad and Helman (1980) have all reported satsifactory trials from feeding both fermented and unfermented 'waste milk' to calves. The data of Keith *et al.* (1981) are presented in *Table 8.6.*

Table 8.6 MEAN (SE) TOTAL FEED INTAKE AND WEIGHT GAIN OF CALVES FED VARIOUS FORMS OF MILK AND WEANED AT 42 DAYS OF AGE

	Milk treatment		
	Normal	*Untreated waste*	*Fermented waste*
Feed intake (kg)	12.1	10.6	14.1
	(1.8)	(1.5)	(2.0)
Weight gain (kg)	19.2	17.6	19.6
	(2.1)	(2.5)	(1.5)

Farmers frequently ask for advice on the use of milk containing antibiotic residues. In New Zealand, Australia and the USA it is often fed to calves, and in Israel one kibbutz collects mastitic milk from several sources, ferments it and rears beef calves very profitably (Gordin, personal communication).

The process of ridding milk of the contaminating antibiotic is simple. If kept above 20°C for 48 h an acceptable level of 0.02 IU/ml results. There are a number of questions to be asked, however; how many farmers will do it, what will it cost and how can we persuade them to do it when no sanction forbids them to feed it direct from the cow? In fact, is there any need to worry whether it is treated or not? The answers to these questions are complex. The number of farmers who will do it depends on whether or not they are convinced that the feeding of antibiotic residues may lead to the production of resistant bacteria and to consequent trouble both on the farm and among the urban population if these bacteria should prove to be both pathogens and zoonoses. The cost will also influence their decision. Trials on a cheap way of holding contaminated milk at the required temperature for the required time are currently being conducted and it is hoped that these will provide appropriate treatments.

Whether there is any harm in feeding non-treated antibiotic contaminated milk is the most important question. It is clear already that the indiscriminate use of antibiotics, both in the medical and veterinary fields is frowned upon. The Swann report recommended a series of controls over the use of antibiotics as growth promoters in feedstuffs, and at a recent meeting of the BVA, Swann called for a new appraisal of the situation. Although the USA papers appear not to worry over the possibilities of the production of resistant bacteria in the feeding of 'waste milk', Yndestad and Helman (1980) note that although results suggest that milk containing antibiotics can safely be fed to calves, effects on drug resistance of bacteria need further investigation. This further investigation is now receiving attention.

In spite of the obvious advantages of *ad-libitum* feeding systems, whether cold or warm, it is probably true that the majority of calf feeders are still feeding once or twice a day, warm or cold, from a bucket. Individual feeding seems still to be preferred and the check on calf health which is so easy when the animal comes to its feed, still enables the majority of calf feeders to keep a closer eye on their charges than so far seems possible with group fed animal on *ad-libitum* systems.

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9

MILK REPLACERS FOR CALVES

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It is only within the past 30 years that man's need for cows' milk has taken priority over the needs of the young calf. The demand for cream and butter, which stimulated a marked increase in milk production throughout Europe in the 1950s, made available large amounts of skim milk, of which some has been utilized in milk replacers for calves. Since that time, the increase in milk production has continued, much of the milk surplus to the liquid market being manufactured into cheese. Recent technological progress in the fractionation of whey has made available new products for human food use and has also given increased scope for the use of whey products in milk replacers for calves.

Despite the high level of subsidy at present paid by the EEC to promote the use of skim milk powder in milk replacers for calves, the cost of skim-based milk replacers is high (>£600/tonne). With alternative cheaper sources of protein available, and spurred on by competition within the animal feed industry, several changes have occurred in the range of milk replacers available during the past six years. Some of these have been introduced in conjunction with new systems of calf rearing (e.g. cold *ad libitum* feeding of acidified milk replacer) or with the advent of automatic 'machine-feeding', but it is pertinent that most milk replacer manufacturers today produce a range of four or even five products, each of which is claimed to be ideal for calf rearing, although the suitability for a particular rearing method (replacement, beef or veal) is generally defined.

In nature, milk is the sole feed of the calf for a few weeks, after which time it is supplemented and then replaced by dry feed as the rumen develops. From soon after birth the calf's digestive system is uniquely adapted for the digestion of cows' milk.

Substitutes for whole milk based on fat-filled skim milk subjected to low heat treatment have given satisfactory results (Roy, 1980a). Those subjected to high heat treatment or containing non-milk proteins have frequently affected the health of the calf during the first three weeks of life, resulting in a greater incidence of diarrhoea, inferior performance and, sometimes, higher mortality. Although in many instances performance has been satisfactory, there are few instances, if any, reported of performance

of calves given such diets being better than that of calves given cows' milk during this initial period. Thus, the whole basis of using milk replacers hinges on their economic advantage to the farmer, and because they permit the convenience of flexibility whereby the stock person can feed the calves at times which do not necessarily coincide with milking time.

Observations made on calves fitted with abomasal pouches and re-entrant cannulas, and measurements of digestibility have contributed greatly to our knowledge of how the calf digests its food. Unfortunately, there is little published information to substantiate some of the claims made on behalf of the milk replacer manufacturers. The main purpose of this chapter is to examine the ways that recent developments in milk replacers relate to the nutrition and health of the calf, particularly the neonate. Some relevant points of discussion are:

(1) the necessity of clot formation in the abomasum of the calf,
(2) the use of non-milk protein sources in milk replacers,
(3) the value of acidification of milk replacer diets.

These topics are not unrelated as they all involve the digestive system of the calf.

The digestive system of the newborn calf

At birth, the digestive system is virtually non-functional and the first few feeds of colostrum obtained from its dam serve to supply the calf with important sources of immune globulins (Ig), energy and vitamins. The large Ig molecules pass rapidly along the small intestine and are absorbed intact by pinocytosis through the walls of the small intestine (Hardy, 1970).

Although little is known of the exact mechanism by which changes in the digestive system occur after birth, it is known that subsequent feeds of colostrum and milk are subjected to a lower pH in the abomasum as gastric acid secretion is stimulated and the rennin/pepsin complex begins to develop (Hardy, 1970). Meanwhile the composition of the mammary gland secretion changes to that of normal milk which in the bovine is untypical in having as much as 80% of the protein in the form of casein micelles in colloidal suspension (Hill, Noakes and Lowe, 1970).

At birth also, the calf leaves the sterile conditions of its mother's womb to become exposed to a multitude of bacteria, viruses and other micro-organisms in its surroundings, including those in the lumen of its alimentary tract. If it fails to exist in a state of mutual harmony with these micro-organisms, the dominance of pathogenic species will give rise to disease.

Escherichia coli is one of the first organisms to become established in the alimentary tract of the normal healthy calf, shortly followed by the lactobacilli which become the most common bacteria in the stomach and small intestines (Smith, 1965). A strain of *E. coli* may proliferate in the intestines of calves given adequate colostrum but subsequently fed a diet which will predispose to diarrhoea (Roy, 1980b; Tzipori, 1981), by adhering to the epithelial cells of the mucosa. The enterotoxins produced and the accompanying erosion of the villi may result in profuse diarrhoea,

loss of ability to absorb water and electrolytes and if this continues will inevitably cause dehydration and death.

Within the alimentary tract of the calf, cows' milk possesses a natural control mechanism in the lactoperoxidase system (Reiter, 1978) but this is destroyed even by mild heat treatment during the spray-drying of skim milk. Nevertheless, provided the neonatal calf is given a diet of inherent high digestibility, such as a good quality milk replacer based on skim milk, the number of organisms such as *E. coli* and rotavirus that colonize the small intestines is kept under control (Roy, 1980a).

Clotting and the digestion of milk

The physiology of digestion in the neonatal calf has been the subject of considerable research effort because of the economic losses that occur as the result of mortality and reduced performance of calves with diarrhoea. The subject has been reviewed by Hill, Noakes and Lowe (1970), Roy and Stobo (1974) and Roy (1980a) amongst others. In summary, when a calf receives a feed of warm milk or a good quality milk replacer based on skim milk, the reticulo-rumen is bypassed as the result of closure of the oesophageal groove and the milk together with saliva enters the abomasum. Clotting of the casein, incorporating the fat, occurs within a few minutes under the action of the chymosin (rennin) present in the stomach before feeding. The muscular contractions of the abomasum help to release the whey fraction, which contains the lactose, minerals and whey proteins including a small quantity of Ig, and which passes into the small intestine where it undergoes digestion under the influence of intestinal enzymes. It has been observed that, for calves given one or two feeds daily, the majority of the whey has passed out of the abomasum within 4 h of ingestion although complete passage may require between 7 and 9 h (Mylrea, 1966a; Ternouth, Roy and Siddons, 1974).

The pH of the coagulum rises after a feed of milk, often to 6.5, due mainly to the excellent buffering capacity of the milk, but as the whey drains off and additional gastric acid is secreted, the pH declines to approach the optimum pH for proteolysis by rennin (3.5) and pepsin (2.1). Meanwhile, continuous muscular contractions of the abomasum assist with mixing and disintegration of the curd.

The lipid fraction is subjected to an initial hydrolysis by the lipase, pregastric esterase, which is present in saliva. Thus, calves which suck milk from a teat are likely to be better equipped to digest lipids than those fed the same diet from a bucket. However, Edwards-Webb and Thompson (1977) suggested that salivary lipase was capable of hydrolysing only the short-chain fatty acids whereas the long-chain fatty acids were digested by pancreatic lipases.

As the clot begins to break up about 6 h after feeding, the partially digested casein and lipid are released into the small intestine, slowly at first but in increasing quantity as time passes. Nevertheless, a large proportion of the clot may still be present 16 h after the meal and may thus be incorporated in the clot formed from a subsequent meal (Ternouth, Roy and Siddons, 1974). Gastric emptying is under neuro-endocrinological

control from sensors sited in the duodenum (Bell *et al.*, 1981), markedly acid conditions causing a rise in blood somatostatin concentrations and inhibiting abomasal emptying. Although Bell (1982) has suggested that the rate of emptying of the abomasum is rapid, with a half-life of between 25 and 35 min, Mylrea (1966a) and Ternouth (1971) have found that with milk diets only 50% of polyethylene glycol as a whey marker is recovered in the first 3 h after a meal.

Digesta are propelled along the intestine by a series of peristaltic movements of its muscular walls. The various nutrients, having been subjected to the initial stages of digestion in the abomasum, undergo further breakdown by enzymes which function best in the more neutral conditions that normally prevail in the small intestine. Absorption of glucose and galactose, amino acids and fatty acids has been shown to occur largely in the duodenum and jejunum (Mylrea, 1966b), although the ileum is also the site of absorption of appreciable quantities of these nutrients in addition to the absorption of endogenous secretions including bile salts (Ternouth, 1971). More caudally, the absorption of water occurs in the large intestine and finally the passage of undigested residues as faeces completes the digestive process. In the healthy calf, the apparent digestibility of protein is about 0.97, of fat is 0.97 and of carbohydrate is 1.0 when cows' milk is fed (Roy, 1977). *Table 9.1* gives the composition of cows' milk and shows that the digestibility is high even from a few days of age.

Table 9.1 COMPOSITION OF COWS' MILK AND APPARENT DIGESTIBILITY OF ITS MAJOR NUTRIENTS BY THE CALF AT DIFFERENT AGES

	Composition	*Apparent digestibility*			
	(g/ℓ)	*7–17 days*[a]	*21–31 days*[a]	*35–45 days*[a]	*28–35 days*[b]
Dry matter	125	0.97	0.97	0.96	0.98
Fat	36	0.95	0.97	0.95	0.97
Crude protein	34	0.94	0.94	0.94	0.95
Lactose	47				1.00
Ash	7.8				0.94
Calcium	1.3				0.93
Phosphorus	1.1				
Sodium	0.4				
Chlorine	0.7				
Gross energy (MJ/ℓ)	2.98				0.97

[a]From Blaxter and Wood (1952a)
[b]From Roy *et al.* (1964)

Unless a milk replacer is capable of being digested almost as efficiently as whole milk, it may well increase the risk of diarrhoea during the neonatal period.

The importance of clot formation for the calf during the first two to three weeks of life is thus to enable the initial process of digestion of casein and fat to take place. There is evidence to suggest that without the abomasal phase of digestion the proteolytic and lipolytic enzyme production in the neonate would be insufficient to enable the casein and lipid to be digested (Gooden, 1973). Moreover, in addition to having a faster rate of passage from the abomasum, diets which do not form a firm coagulum, such as heat treated milk and non-milk protein ingredients, result in depressed secretion of gastric acid and enzymes (Williams, Roy and Gillies, 1976) and reduced pancreatic proteolytic enzymes (Ternouth, Roy and Siddons,

1974). The passage of undigested protein into the intestine has been associated with diarrhoea in calves, although the severity of the disease may be dependent upon the immune status of the calf and the burden of infection in the environment, which in turn may be affected by the number of calves in a calf house that are receiving a detrimental diet (Roy, 1975; 1980b). 'Severely' preheated skim milk powders and non-milk proteins do not coagulate *in vitro* or *in vivo* in the conditions occurring in the abomasum (Tagari and Roy, 1969; Ternouth *et al.*, 1975; Lister and Emmons, 1976) and the reduced abomasal retention time of both skim milk and non-milk proteins has been highlighted as the cause of reduced digestibility of protein and of lipid (Guilloteau, Toullec and Patureau-Mirand, 1979).

Attempts to improve the 'coagulating-properties' of milk replacers containing heat-treated skim milk and non-milk proteins by the use of salts of calcium or magnesium have not, in general, been a great success. A recent study in Canada, however, has shown that low-pressure dispersion of lipid (tallow and coconut mixture) into reconstituted skim milk resulted in significantly greater curd firmness values with rennet than when the mixture of skim milk and lipid was mechanically homogenized to produce fat globules below 1 μm in diameter, as opposed to a variety of sizes between 1 and 20 μm with low pressure dispersion (Jenkins, Emmons and Lessard, 1981). One feature of this work was that, unlike the commercial situation in which generally the fat is homogenized into only a small proportion of the skim milk, the Canadian workers treated all the diet. This may possibly have had the effect of coating the protein with fat and thus preventing the vital linkage of β-lactoglobulin and casein so necessary in clotting of milk. A similar beneficial effect was reported for diets in which up to 40% of the skim milk was replaced by a mixture of fish protein concentrate and whey or by a mixture of isolated soya protein and whey. Although apparent digestibility was claimed to be 0.97, 0.94 and 0.91 for dry matter, nitrogen and lipid respectively (Jenkins and Emmons, 1979), it was unfortunate that the extraction method used to determine faecal lipids was unlikely to have effected complete hydrolysis of the lipid bound in calcium and magnesium soaps. Nevertheless, the health and performance of the calves on the diet prepared with low-pressure dispersion merits further examination of the technique as a means to improve coagulability of milk replacers for calves during the first two to three weeks of life.

As a possible safeguard against the digestive upsets that can occur following the passage of undigested protein from the abomasum to the small intestine, many milk replacers commercially available contain one or more of the permitted antibiotics as a preventative measure. The prophylactic use of antibiotics has been viewed with concern by some advisers on calf husbandry and welfare and the subject was discussed at the centenary celebrations of the British Veterinary Association, because of the implications of the development of antibiotic resistance in bacteria. Despite this concern, the use of antibiotics is unlikely to decline voluntarily, as the proportion of milk replacers containing non-milk proteins increases at the expense of skim milk. Nevertheless, these newer products based on whey and non-milk protein sources are claimed to be successful. Before examining this type of milk replacer in greater detail, it is pertinent to relate the composition of milk replacers to the nutrient requirements of the calf.

Nutrient requirements of the neonatal calf

Since cows' milk is capable of supporting a rate of gain in the calf within the range of maintenance only up to 1.5 kg/day, especially if fortified with vitamins and trace minerals plus magnesium, the obvious starting point for the formulation of milk replacers is with the composition of cows' milk (*Table 9.1*).

PROTEIN CONCENTRATION IN THE DIET

On a dry matter basis, milk contains approximately 269 g crude protein/kg. In relating the protein requirement of the preruminant calf (by summation of its nitrogen balance over a range of liveweight gain with the requirements for endogenous urinary N excretion and metabolic faecal N excretion) to its intake of dry matter, Roy (1977) concluded that a protein concentration of 260 g/kg dry matter would be adequate even for the fastest rate of gain required above 50 kg live weight, and that a crude protein concentration of 200 g/kg dry matter was adequate above 100 kg live weight. Roy *et al.* (1970) had previously shown that a crude protein concentration of 193 g/kg dry matter in a milk substitute diet fed *ad libitum* to veal calves was unable to support as high weight gains as when the protein concentration was 263 g/kg dry matter. With the low-protein diet, feed intake was reduced, but so too were both the digestibility of protein and the amount of nitrogen retained per unit of liveweight gain.

Whereas a protein concentration of 260 g/kg dry matter seems appropriate for the veal calf (van Weerden, van Es and van Hellemond, 1970) it is unlikely to be excessive for maximum efficiency of protein utilization in calves being fed at a maintenance level with the intention of weaning on to solid feed at five to six weeks of age. This, however, assumes that the protein source in the replacer is adequately balanced for amino acids. If there is a shortage of one or more essential amino acids (EAA) excess protein can be useful in supplying the EAA that is deficient as well as being used to supplement the energy supply.

The suitability of milk protein for the young calf is apparent not only from its high digestibility (true digestibility 1.0; apparent digestibility 0.97 at one week of age (Roy, 1980a)), but also from its biological value which may be as high as 0.92 (Blaxter and Wood, 1952b; Brisson, Cunningham and Haskell, 1957). Thus, although it has been suggested that cows' milk is slightly deficient in sulphur-containing amino acids (Robert, 1971) little is known of the exact requirements of the preruminant calf for individual amino acids. Data are available for the amino acid composition of the carcase, but the turnover rates of individual amino acids are likely to differ and live weight and rate of weight gain might further complicate the situation. An accurate estimate of the EAA requirements would need to resort to the use of the slow and tedious method of measuring the response in plasma amino acid and plasma urea concentrations to given levels of a single amino acid which must be the first limiting EAA in the diet. Williams and Hewitt (1979) estimated the amino acid requirements of the preruminant calf by first determining the lysine requirements as suggested

Table 9.2 ESTIMATED ESSENTIAL AMINO ACID REQUIREMENTS (g/DAY) OF THE PRERUMINANT CALF (50–58 kg LIVE WEIGHT) GROWING AT 0.25 kg/DAY, AND THE CONCENTRATION IN SKIM MILK, WHEY PROTEINS AND SOME NON-MILK PROTEIN SOURCES (g/16 g NITROGEN)

	Estimated requirements of the calf[a]	*Skim-milk powder*	*Whey powder*	*Soya protein concentrate*	*Fish protein hydrolysate*[b]	*Bacterial protein (Pruteen)*[c]
Crude protein concentration (g/kg dry matter)		360	130	700	900	780
Lysine	7.8	7.7	5.2	6.2	8.8	5.8
Methionine	2.1	2.4	1.3	1.3	3.8	1.9
Cystine	1.6	1.2	2.3	1.5	1.4	0.7
Threonine	4.9	4.6	5.9	4.0	4.8	4.7
Valine	4.8	7.4	5.5	5.0	4.8	5.6
Isoleucine	3.4	5.5	5.1	5.0	4.3	4.7
Leucine	8.4	11.6	9.7	7.6	7.3	7.3
Tyrosine	3.0	4.8	2.4	3.7	—	3.0
Phenylalanine	4.4	4.9	2.8	5.0	—	3.6
Histidine	3.0	2.5	1.3	2.5	—	1.8
Arginine	8.5	3.7	2.0	7.2	6.0	5.2
Tryptophan	1.0	1.4	1.6	1.5	—	1.4

[a]From Williams and Hewitt (1979)
[b]From Petchey (1982)
[c]From ICI plc

above and then estimating the other EAA requirements from the ratio of EAA:lysine in the body, determined by carcase analysis. Although their results are open to criticism, they are presented in *Table 9.2*, where they appear alongside the amino acid profiles of some dietary ingredients commonly used in milk replacer diets for calves. On the basis of their findings, Williams and Hewitt (1979) concluded that the preruminant calf would probably be deficient in EAA only when given diets in which milk protein is replaced by substantial amounts of non-milk proteins. However, whey protein, which is being increasingly used in formulating milk replacers, has a methionine concentration of only 1.3 g/16 g nitrogen compared to 2.4 g for skim-milk powder. Nevertheless, the total concentration for the sulphur amino acids, methionine plus cystine, is almost identical in the two products; no difference in performance of calves has been observed when milk substitute diets containing 260 g crude protein and 200 g fat/kg dry matter were fed, irrespective of whether skim-milk powder or whey proteins either alone or in various combinations supplied the protein source (Stobo, unpublished). Although supplementary methionine is normally recommended when soya protein is included in milk replacers for calves, Gorrill and Nicholson (1969) could find no benefit when dry food was also available. In the absence of further information, it would seem reasonable to supplement all non-milk protein sources used in milk replacers to bring the level of EAA up to that present in skim milk. Even if this is done, protein allowances should possibly be increased slightly to allow for reduced digestibility and lower biological values when high levels of non-milk protein are incorporated.

FAT CONCENTRATION IN THE DIET

The concentration of butter fat in cows' milk is 280 g/kg dry matter; nevertheless this fraction supplies 45% of the energy, with the protein and lactose supplying almost equally the remaining 55%. Although the advantage of this level of fat in the diet of the calf is that it will promote the deposition of body fat, which accumulates in the young ruminant at a faster rate than protein (Walker, 1979), substitutes for milk fat are not so highly digestible and therefore lower quantities tend to be included. Despite this, there is ample evidence to support the idea that in milk replacer diets, the higher the fat concentration within the range 10–300 g/kg dry matter of a readily digested fat, the greater the build up of body reserves that can be drawn on when the calf is weaned (Roy, 1980a) and the greater the protective effect against infection (Stobo *et al.*, 1982).

The choice of alternative fat sources to be included in commercial milk replacers is largely a matter of economics, with animal fats being generally cheaper than vegetable oils. Tallow is relatively poorly digested by the calf, due mainly to the low digestibility of saturated palmitic and stearic acids (Raven and Hamilton, 1971). There is considerable improvement in digestibility with age and also by the inclusion of palm oil or coconut oil, although the latter may give rise to an increase in susceptibility to pneumonia (Roy *et al.*, 1973) unless the shortage of essential fatty acids is made good. It is imperative to obtain the right balance between essential fatty acid concentration and vitamin E level, which has been demonstrated to be between 1.5 and 2.5 mg vitamin E/g linoleic acid (Hartfiel, 1967). The inclusion of additional lecithin may be beneficial in improving the digestibility of homogenized tallow, although with lipid sources that have a high digestibility little benefit is likely to accrue from the use of more than 10 g soyabean lecithin in 200 g fat.

CARBOHYDRATE CONCENTRATION IN THE DIET

The lack of enzyme activity in the alimentary tract of the neonatal calf for hydrolysis of any carbohydrate other than lactose severely limits the choice of carbohydrate type that can safely be used in milk replacers to be fed during this early stage. Even so, it has been suggested that the calf can only tolerate a total 'hexose equivalent' (the sum of the weight of glucose and the weight of lactose × 1.05 (Walker and Faichney, 1964)) of 9 g/kg live weight, although with high fat diets a value of 12 g/kg may be more appropriate, before diarrhoea arising from fermentation in the large intestine would become a problem.

The inclusion of 20 g starch/kg dry matter in milk replacers containing at least 600 g skim milk powder/kg is necessary if the EEC subsidy on skim-milk powder is to be claimed. Maize starch is commonly used, but wheat, potato and cassava may also be the source of the raw material. Many products are processed to partially gelatinize them into a mixture of glucose polymers, which allows them to remain in suspension in the reconstituted milk replacer, but the process is also aimed at converting the starch into a form that is suitable for digestion by the amylolytic enzymes

Table 9.3 EFFECT ON THE PERFORMANCE AND DIGESTIBILITY OF THE DIET BY THE YOUNG CALF OF INCLUSION OF 20 g MAIZE STARCH/kg IN A MILK REPLACER BASED ON SKIM MILK

	Skim based milk replacer	*Skim based milk replacer + starch*	*Pooled SE*	*Probability*
Dry matter intake (kg/day)				
0–14 days	1.06	0.94	0.048	$P = 0.102$
14–28 days	1.30	1.20	0.066	$P = 0.311$
Liveweight gain (kg/day)				
0–14 days	0.74	0.47	0.091	$P = 0.062$
14–28 days	1.16	1.07	0.088	$P = 0.454$
Apparent digestibility				
Crude protein				
1 week	0.90	0.85	0.015	$P = 0.077$
4 weeks	0.92	0.88	0.021	$P = 0.185$
Carbohydrate				
1 week	0.99	0.97	0.003	$P = 0.036$[a]
4 weeks	0.99	0.98	0.003	$P = 0.247$

[a]Significant difference

present in the digestive tract of the young calf. Nevertheless, Stobo *et al.* (1976) reported a reduction in liveweight gain and a significant reduction in apparent digestibility of carbohydrate and of protein and in nitrogen retention in the period 7 to 14 days of age when 20 g starch/kg dry matter was included in the milk replacer diet (*Table 9.3*). In milk replacers containing 350 g of a thermo-alkali treated soya flour, the inclusion of 150 g of a wheat and maize carbohydrate complex with added amylolytic enzymes, sorbitol and a coagulant (Protamyl 110), together with 150 g whey powder/kg milk replacer, gave similar weight gains in calves as occurred when the diet contained 300 g whey powder/kg and no Protamyl (Roy *et al.*, 1978). As shown in *Table 9.4*, the performance was considerably below that of calves given a diet based on milk protein; this might be

Table 9.4 EFFECT OF MILK PROTEIN (M) OR OF SOYA PROTEIN (S) WITH EITHER WHEY POWDER (W) OR A MIXTURE OF WHEY AND PROTAMYL 110 (WP), WITH OR WITHOUT ADDITIONAL CALCIUM AND PHOSPHORUS, ON PERFORMANCE AND DIGESTIBILITY IN FRIESIAN CALVES GIVEN MILK REPLACERS *AD LIBITUM* FROM TWO DAYS OF AGE TO A LIVE WEIGHT OF 136 kg

Diet	M	SW	SW	SWP	SWP
Ca and P supplement	−	−	+	−	+
Mean DM intake	1.62	1.50	1.66	1.54	1.62
Liveweight gain (kg/day)	1.10	0.74	0.79	0.74	0.78
Apparent digestibility					
Dry matter 1 week	0.88	0.61	0.60	0.59	0.59
4 weeks	0.94	0.79	0.74	0.74	0.72
10 weeks	0.94	0.84	0.80	0.82	0.80
Protein 1 week	0.82	0.37	0.39	0.33	0.34
4 weeks	0.91	0.64	0.59	0.61	0.55
10 weeks	0.92	0.72	0.68	0.69	0.63
Carbohydrate 1 week	0.98	0.83	0.83	0.76	0.78
4 weeks	0.99	0.90	0.89	0.87	0.85
10 weeks	1.00	0.91	0.89	0.88	0.89

(From Roy *et al.*, 1978)

attributed to the low digestibility of all nutrients, including carbohydrate, especially at a young age.

For the older calf, considerable research has indicated that a mixture of raw and processed starches can be safely introduced up to an inclusion rate of 150 g/kg (Toullec, Theriez and Thivend, 1980), although they must be introduced gradually if diarrhoea is to be avoided. Thus for practical purposes milk replacers intended for general use should not contain more than the statutory minimum of 20 g/kg in order to claim the subsidy.

Specification of a milk replacer diet

Successful formulation depends on providing a diet that will supply the needs of the calf at reasonable cost. In addition to supplying a high-energy diet balanced in protein, lipid and carbohydrate, milk replacers need to be fortified with trace minerals, vitamins A, D and E, possibly biotin and vitamin B_{12} and magnesium. Appropriate supplement inclusion rates are well documented elsewhere (*see* Roy, 1977; Roy and Stobo, 1978; Roy, 1980a) and will not receive attention here. The milk replacer needs to be palatable, easily mixed (in cold water if necessary as part of a calf rearing system), remain in suspension when mixed, of high inherent digestibility and have a good efficiency of conversion into body tissue. Despite the fact that the nutrient requirements of the calf demand a change in the composition of its diet according to its live weight and desired level of performance, once a calf has been given a particular milk replacer diet it will normally remain on that diet until it is weaned or, if a veal calf, until it has reached two to two and a half months of age.

Alternatives to skim milk

SOYABEAN PROTEIN

Judged solely on the basis of price and availability, soyabean protein has commercially the greatest potential as a replacement for milk protein in the diet of the milk-fed calf. Attempts have been made to substitute skim-milk protein by soyabean protein for at least 50 years, generally without success, since calves have been reported to suffer diarrhoea, loss of appetite, high mortality and poor growth if they survive (e.g. Shoptaw, 1936; Williams and Knodt, 1950). Removal of soyabean oil (Raven, 1970), supplementation with methionine (Gorrill and Nicholson, 1969) and destruction of trypsin inhibitors and haemagglutinins by steaming or toasting (Gorrill and Thomas, 1967; Nitsan *et al.*, 1972) or by treatment with acid or alkali (Ramsey and Willard, 1967), have been unable to produce a soya flour that was as satisfactory as milk protein.

Soya flour contains about 300 g oligosaccharides/kg, that are probably unavailable to the preruminant calf; their extraction results in a soya protein concentrate (SPC). Results from the inclusion of SPC in milk replacers have been variable and sometimes disappointing, with poor performance and low digestibility of protein being common features when

calves were given a milk replacer containing SPC before seven to ten days of age and in the absence of dry food (Nitsan *et al.*, 1972).

Studies on calves fitted with cannulas in various parts of the alimentary tract have provided a greater understanding of the problem. In calves that have received several feeds containing soyabean flour, a marked inhibition of abomasal emptying develops (Sissons and Smith, 1976) followed by a decrease in transit time of digesta through the small intestine. Other changes that occur include a reduction in gastric acid and enzyme secretion (Colvin, Lowe and Ramsey, 1969; Williams, Roy and Gillies, 1976), a reduction in pancreatic protease secretion and the passage of undigested protein into the small intestine (Ternouth, Roy and Shotton, 1976). Thickening of the walls of the small intestine of calves given soya-containing diets was reported by Roy *et al.* (1977); this could be the result of a gastrointestinal allergy as suggested by Smith and Sissons (1975). Support for this idea occurred when IgG antibodies specific for the soya bean globulins, glycinin and β-conglycinin, were detected in the serum of calves given diets containing soyabean protein (Smith and Sissons, 1975; Barrett, Strachan and Porter, 1978; Kilshaw and Sissons, 1979; Kilshaw and Slade, 1980). Moreover, the severity of digestive disorders in animals

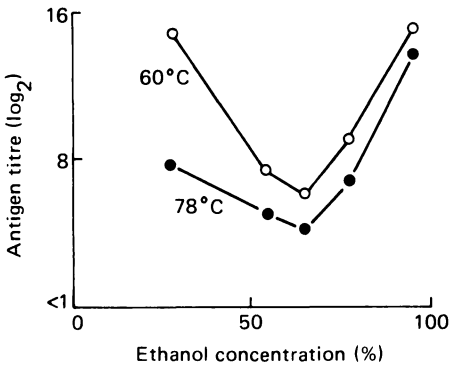

Figure 9.1 Effect of concentration of ethanol in water and of temperature of extraction on the antigenic activity of glycinin in a soya protein concentrate

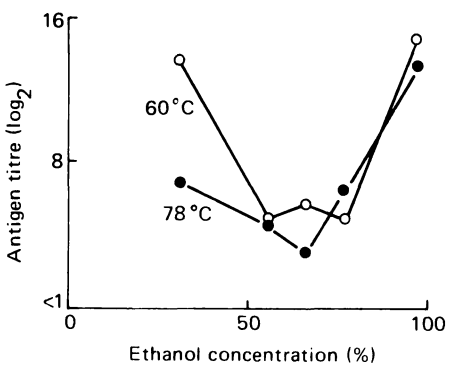

Figure 9.2 Effect of concentration of ethanol in water and of temperature of extraction on the antigenic activity of β-conglycinin in a soya protein concentrate

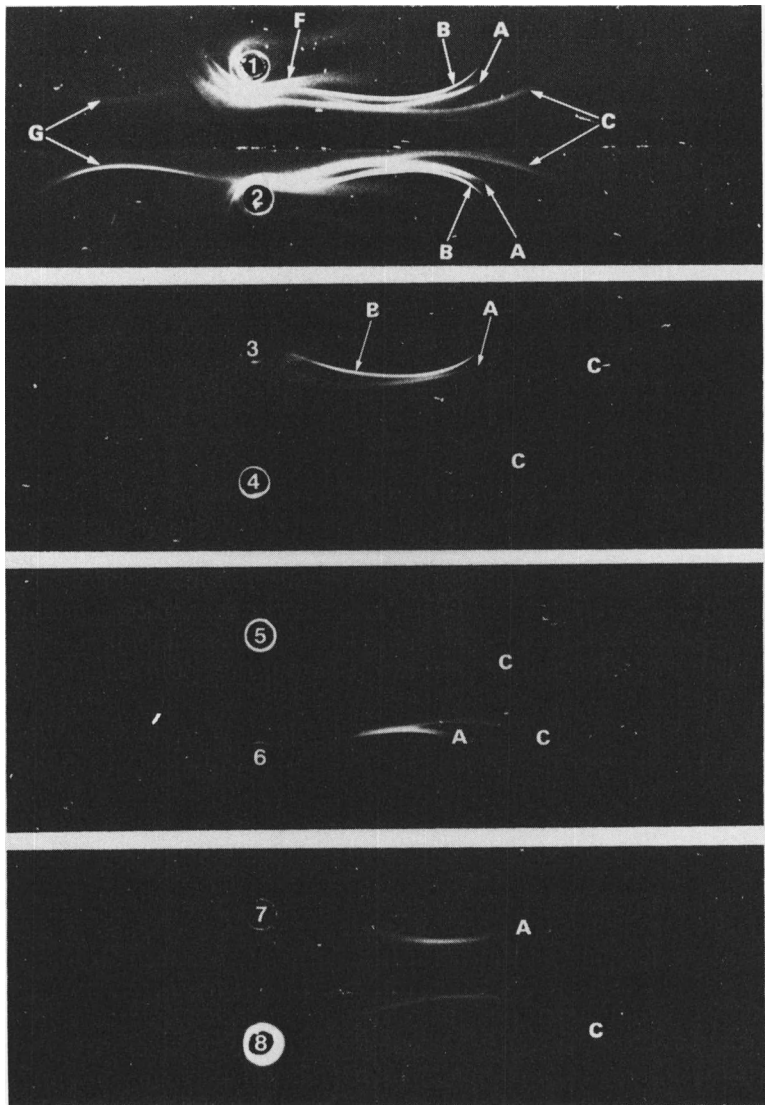

Figure 9.3 Immunoelectrophoresis of saline extracts of various processed soyabean products. Precipitates were developed with IgG prepared from rabbit antiserum raised against an extract of unprocessed soyabean flour. 1 and 2 Heated soya flour. 3 Acid and alkali treated soya flour. 4 Ethanol extracted (75% at 80 °C for 2 h) SPC. 5 Ethanol extracted (between 60 and 80% at about 65 °C) SPC. 6 Water and steam extracted SPC. 7 Acid precipitated soya protein isolate. 8 Ethanol extracted (60–80% at about 65 °C) SPC. A, Glycinin; B, β-conglycinin; C, trypsin inhibitor; F and G, unidentified constituents. (Reproduced by kind permission of P.J. Kilshaw and J.W. Sissons, 1979)

given diets containing soya products processed in a variety of ways was related to the antibody titre (Smith and Sissons, 1975).

Even soya protein concentrates were found to contain antigens unless they were prepared by extraction using hot aqueous ethanol. Sissons *et al.* (1982a) have further shown that both the concentration of ethanol in water and the temperature of extraction are critical if destruction of the antigenically active glycinin and β-conglycinin is to reach its maximum (*see Figures 9.1* and *9.2*). The recommended conditions are a concentration of between 55 and 76% ethanol at temperatures between 70 and 80 °C, failing which there is likely to be incomplete extraction of the two antigens. Thus it seems probable that much of the discrepancy that has been apparent between experiments made with calves given different soya protein concentrates may have been associated with different levels of antigens. The antigens can be detected in the soya products by means of immunoelectrophoresis, as described by Kilshaw and Sissons (1979), and are confirmed by comparison with the antigens in antiserum prepared in rabbits. The results of Kilshaw and Sissons (1979) are reproduced in *Figure 9.3* to show how various soya products differ in their content of the antigens glycinin and β-conglycinin.

Commercial production of antigen-free SPC relies on a large scale processing plant with a high throughput. Such conditions make it difficult to ensure complete destruction of the antigens and rigorous monitoring is therefore necessary. The immunochemical test of Sissons *et al.* (1982b) would seem to be the basis for effective quality control of the antigen level in soya products for use in milk replacers for the calf.

A commercially available antigen-free SPC (Soycomil K (Unimills, Hamburg)), has recently been reported to have given as good performance in Friesian calves from one week of age as that achieved by a control group given a skim-milk based diet, at an inclusion rate of 230 g SPC/kg whey-based milk replacer (Thomas, 1982). The calves were given access to dry food and were weaned after nine weeks on the experiment. Although 60% of the protein was supplied by the SPC, feed conversion ratio was no different from that for the control diet during the first five weeks of the trial (1.80 and 1.74 kg powder/kg weight gain respectively). Our own trials at present in progress suggest that when the same SPC provides only 35% of the protein, digestibility is reduced at one week of age but thereafter improves (Stobo, unpublished), although even 70% of the protein from SPC has not caused digestive upsets.

FISH PROTEINS

Although results of experiments have suggested that fish protein concentrate (FPC) was, in general, more satisfactory than many of the earlier soya products (*see* reviews by Huber, 1975 and Roy, 1980a), little use appears to have been made of fish protein in milk replacer diets for the calf. Recently, attempts have been made to revive interest in the use of fish protein hydrolysates (FPH) following technological developments which allow controlled enzyme breakdown of the fish protein into amino acids and peptides, which are largely water-soluble (Mackie, 1982). FPH prepared

Table 9.5 UTILIZATION OF PROTEINS FROM DIFFERENT SOURCES BY THE PRERUMINANT CALF

Protein source	*Protein content of diet* (g crude protein/kg dry matter)	*Proportion of protein supplied by product*	*Age* (weeks)	*Apparent digestibility of total protein in diet*	*Reference*
Cows' milk	272	1.00	1–5	0.97	*see Table 9.1*
Liquid skim milk	359	1.00	4–5	0.94	Roy, Stobo and Gaston (1970)
Reconstituted spray-dried fat-filled skim-milk powder	299	1.00	4–5	0.94	
'Severely' heat treated fat-filled SMP	247	0.92	(3–10 days)	0.63	Shillam and Roy (1963)
'Mildly' heat treated fat-filled SMP	247	0.92	(3–10 days)	0.75	
Spray-dried whey powder	264	0.05	1–2	0.88	Roy *et al.* (1970)
			4–5	0.90	
Whey concentrated by ultrafiltration			3	0.87	Toullec, Theriez and Thivend (1980)
			4–11	0.94	
Soya bean					
Full-fat, unheated	287	0.40	2–3	0.53	Nishimatsu and Kumeno (1966)
			5–6	0.76	
Defatted, heated	170	0.35	3–4	0.76	McGilliard *et al.* (1970)
			7–8	0.85	
Defatted, heated, alkali-treated	291	0.36	1–2	0.78	Roy *et al.* (1977)
			4–5	0.84	
	282	0.70	1–2	0.66	
			4–5	0.64	
Concentrate, extracted,					
raw	321	0.82	4	0.77	Nitsan *et al.* (1971)
partly heated	321	0.82	4	0.82	
heated	300	0.82	4	0.90	
Isolate		1.00	1–2	0.75	Porter and Hill (1963)
		1.00	4–5	0.87	

Fish, flour	220	0.33	1–2	0.86	Huber and Slade (1967)
			6–7	0.91	
		0.67	1–2	0.84	
			6–7	0.90	
		1.00	1–2	0.80	
Concentrate	288	0.33	1–2	0.77	Roy *et al.* (1977)
			4–5	0.84	
	270	0.61	1–2	0.69	
			4–5	0.77	
Concentrate (hydrolysate)	271	0.73	2–3	0.82	Paruelle *et al.* (1974)
			4–5	0.89	
Concentrate (partially hydrolysed)	256	0.50	1–2	0.93	Jenkins *et al.* (1982)
	302	0.80	1–2	0.93	
Dried bacterial cells	284	0.22	1–2	0.79	Stobo and Roy (1977)
			4–5	0.88	
	305	0.44	1–2	0.77	
			4–5	0.85	

from fatty fish was not satisfactory, but that prepared from white fish (cod, blue whiting and white fish offal) given as the entire protein source to Friesian male calves from four days of age until they were weaned at 42 days was viewed favourably by the author (Petchey, 1982), who confidently predicted that FPH could replace one-third of skim milk in milk replacers for early-weaned calves.

Studies using FPH have shown that protein digestibility is in the region of 0.8–0.9 when up to 75% of the protein was supplied by the FPH (Paruelle *et al.*, 1974; Gorrill *et al.*, 1975; Toullec, Coroller and Patureau-Mirand, 1977), with a significant improvement with age. Nevertheless, the protein digestibility of FPH is higher than that reported for FPC by Roy *et al.* (1977) and in the experiment reported by Jenkins *et al.* (1982) digestibility of nitrogen was 0.93 between 6 and 13 days of age when FPH supplied 50 or 80% of the dietary protein in the milk replacer given to calves weaned at four to five weeks of age. The failure of veal calves to perform well on these same diets was attributed by Jenkins *et al.* (1982) to a shortage of essential amino acids, notably tryptophan, histidine (or its low availability), isoleucine and valine. Nevertheless, fish protein has high levels of sulphur amino acids and, in combination with whey and soya proteins, might be considered to be a useful replacer for skim milk provided digestibility during the neonatal period could be raised to that of skim milk.

SINGLE CELL PROTEIN

In common with other non-milk protein sources, single cell protein (SCP) has a reduced digestibility of protein when included in milk replacers given to calves at a young age (*see Table 9.5*). Although 22% of the protein supplied by bacterial protein (Pruteen, ICI plc) (an inclusion rate of 100 g/kg) supported weight gains of 1.1 kg/day to 12 weeks of age, 44% protein from Pruteen caused a reduction in liveweight gain (Stobo and Roy, 1977). Hinks (1977) reported that whereas inclusion rates of 50 and 100 g Pruteen/kg dry matter in milk replacer diets given to seven-day old Friesian calves were satisfactory, one of 200 g/kg resulted in severe diarrhoea. However, whether the high level of Pruteen was really responsible for the digestive upset is not clear, since this diet also contained 134 g maize starch/kg dry matter.

Sedgman (1980) has shown that the reduced digestibility of SCP in the young calf was associated with a reduction in gastric acid and enzyme secretion, reduced proteolysis by gastric enzymes, increased flow of undigested protein at the duodenum and poor absorption of amino acids from the small intestine. In addition, the efficiency of retention of absorbed nitrogen was also lower than with milk protein. This latter view does not accord with the finding of Hinks (1978), who suggested that the efficiency of retention of absorbed nitrogen was higher in calves given a diet containing 100 g Pruteen/kg than in those given a control diet containing 600 g skim milk solids/kg, but which had a lower feed intake and grew at a slower rate.

The lower protein digestibility observed by Stobo and Roy (1977) in

calves at one week of age when given diets containing Pruteen was no longer apparent at four weeks of age when the inclusion rate of Pruteen was 100 g/kg dry matter, or at ten weeks when the milk replacer contained 200 g Pruteen/kg. This would explain the failure of van Weerden and Huisman (1977) to find any difference in protein digestibility between milk replacer diets containing 200 g Pruteen/kg or none, when given to veal calves at eight and 15 weeks of age.

Although it is apparent that the calf can probably tolerate up to 100 g Pruteen/kg milk replacer from immediately after the colostrum-feeding period, the reduced digestibility at a young age suggests that the risks associated with its inclusion, in common with other non-milk protein sources, are likely to be higher than when the neonatal calf is given a diet based on good quality milk protein. There may be advantages in mixing two or more non-milk protein sources when it is decided to include these.

WHEY PRODUCTS

There are essentially four categories of liquid whey; sweet wheys which are by-products of the production either of soft continental cheeses or of hard cheeses, using rennet coagulation, and acid wheys from the production of acid coagulated cheeses or from the preparation of casein. The chemical composition is shown in *Table 9.6*.

Table 9.6 ANALYSIS OF SOME TYPICAL CHEESE WHEYS

	Sweet (continental) whey	*Hard cheese (cheddar) whey*	*Acid (cottage cheese) whey*	*Acid (casein) whey*
Total solids %	6.7	6.7	5.0	6.5
Fat	0.4	0.4	0.1	0.1
Protein (N × 6.38)	0.9	0.8	0.6	0.9
Lactose	4.8	4.9	3.4	4.6
Ash	0.5	0.6	0.5	0.6
Total acid (as lactic acid)	0.16	0.15	0.35	0.40
pH	6.1	5.9	4.5	4.5

(From Parkinson, 1980)

All types of whey can be processed and dried, but when acid whey is neutralized with sodium hydroxide and subsequently processed into delactosed whey powder it can have an extremely high sodium concentration (*Table 9.7*). Unconfirmed reports have suggested that mortality in calves may be the result of sodium poisoning, for which the high sodium concentration in delactosed whey might possibly be implicated. This may be only one reason why milk replacer manufacturers prefer to use sweet whey that originates from continental cheese making; most French and Dutch wheys are considered to be greatly superior to British whey products for calf feeding.

Considerable technological advances during the last few years now enable much of the 1500 million ℓ of liquid whey produced in the UK to be processed, whereas in 1976 it was either fed to pigs or discharged through

effluent plants (Parkinson, 1980). Processing methods include fractionation using ion exchange or electrodialysis to remove minerals, or more important, ultrafiltration through semipermeable membranes to form protein-rich and lactose-rich fractions. Further, recent improvements in low-temperature concentration by evaporation make possible the production of a range of dried whey, delactosed whey and whey protein concentrates (WPC) in which the protein has not been denatured by heat and should therefore be ideal for use in milk replacers for the calf. Because of the demand for WPC in the human food industry, economics dictate that the protein concentration of a typical WPC used in calf diets should be only about 350 g/kg. The composition of various dried whey products, together with skim milk and some non-milk protein products, is given in *Tables 9.7* and *9.8*.

In spite of the new technology, some whey and skim-milk powders are denatured by excessive heat treatment and are not suitable for the calf. In such products, a variety of physical tests can be used to determine quality

Table 9.7 CHEMICAL COMPOSITION OF SKIM-MILK POWDER AND SOME WHEY PRODUCTS THAT MIGHT BE USED IN FORMULATING MILK REPLACER DIETS FOR CALVES (g/kg)

	Skim-milk powder	*Whey powder*	*Delactosed whey*	*Whey protein concentrate*
Dry matter	980	979	970	968
Composition of dry matter (g/kg)				
Fat	24	13	10	28
Protein (N × 6.38)	363	137	260	363
Lactose (anhydrous)	519	695	496	480
Ash	82	85	189	77
Calcium	13.5	5.9	26.1	8.8
Phosphorus	9.4	6.4	13.3	6.6
Sodium	6.1	10.6	15.9	11.2
Chlorine	18.7	30.0	58.4	21.3
Gross energy (MJ/kg)	18.0	15.2	14.6	18.3

Table 9.8 CHEMICAL COMPOSITION OF SOME NON-MILK PROTEIN INGREDIENTS THAT MIGHT BE USED IN FORMULATING MILK REPLACER DIETS FOR CALVES (g/kg)

	Defatted soya flour	*Soya protein concentrate*	*Fish protein hydrolysate*	*Bacterial protein*
Dry matter	914	946	930	940
Composition of dry matter (g/kg)				
Fat	45	13	28	140
Protein (N × 6.25)	544	702	892	746
Carbohydrate	292	161	0	0
Fibre	52	53	0	<10
Ash	68	71	70	102
Calcium	2.8	4.4	1.6	14
Phosphorus	7.4	9.1	3.2	23
Sodium	0.2	0.6	2.5	2
Chlorine	1.5	—	3.5	0.3
Gross energy (MJ/kg)	19.9	19.5	22.3	20.4

(*see* Mettler, 1980), but chemical changes can be detected by measurement of the non-casein nitrogen fraction which in milk declines from 23% of total nitrogen in untreated milk to 10% in milk heated to 90 °C for 30 min. A minimum value of 18% is acceptable in skim milk to be used in milk replacers for the calf.

Corresponding values for whey products would decline as denaturation increases, from a theoretical maximum value of 100% in fresh whey. However, since approximately 24% of whey nitrogen is in the form of non-protein nitrogen, 10% of the total nitrogen is in the form of proteose–peptone nitrogen and further proteose–peptone is produced by the action of chymosin on milk, even the most severely heat treated whey protein would have a non-casein nitrogen value of about 40%. A good quality whey powder should contain 90% non-casein nitrogen on analysis.

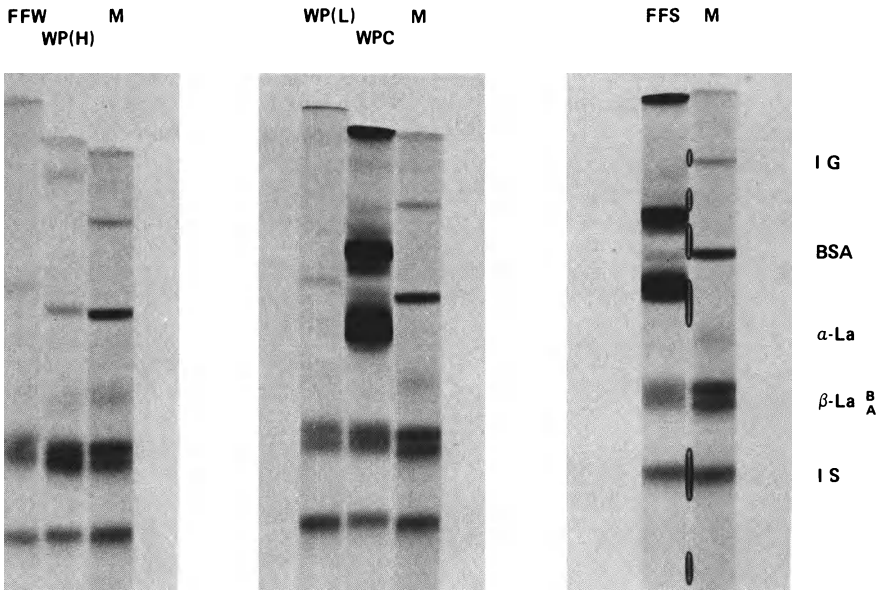

Figure 9.4 Polyacrylamide gel electrophoresis of whey proteins obtained from several sources. FFW, fat filled whey powder (500 g fat/kg); WP(H), spray-dried whey powder (high heat treatment); M, whey from whole milk (control); WP(L), spray-dried whey powder (low heat treatment); WPC, whey protein concentrate powder (350 g protein/kg) (severely denatured); FFS, fat-filled skim milk powder (200 g fat/kg). IG, immune globulin; BSA, bovine serum albumin; α-La, α-lactalbumin; β-La^{B}_{A}, β-lactoglobulins B and A; IS, internal standard

Attempts have been made to determine the extent of heat denaturation of whey and skim-milk solids by polyacrylamide gel electrophoresis, based on the method of Hillier (1976). This technique separates out the whey proteins into γ-globulins, bovine serum albumin and α- and β-lactoglobulin fractions. By comparison with the values obtained from an undenatured cows' milk, the concentration of each fraction can be determined and the extent of denaturation determined. *Figure 9.4* merely serves to illustrate the type of gel produced by the technique when various whey products and a fat-filled skim-milk powder are compared with a milk

standard. The height of the peaks at the specific molecular weights of the fractions is measured so that, for example, the large amounts of high-molecular weight proteins seen with one of the fat-filled products and with the WPC in *Figure 9.4* would not complicate the issue.

Choice of ingredients in formulating a milk replacer

In spite of the arguments in favour of a good clot formation in the abomasum of the neonatal calf in particular, reports suggest that the proportion of milk replacers based on skim-milk powder is declining both in the UK and in Europe in favour of cheaper products containing non-milk ingredients and whey products, even though these replacers do not attract the subsidy payable when skim milk is used at a minimum inclusion rate of 60%. There are few digestibility data so far available to help to substantiate claims that some of the recently-introduced products are highly digestible. It appears to be relevant that, in an attempt to improve protein digestion, Jenkins, Mahadevan and Emmons (1980) conducted an *in vitro* study to assess the hydrolytic susceptibility of various milk and non-milk proteins (soyabean, rapeseed and fish) used in calf milk replacers to endogenous and commercial proteolytic enzymes. As shown in *Table 9.9*, both at pH 6.1 and at their optimum pH, the various enzymes

Table 9.9 EXTENT OF HYDROLYSIS (%) OF MILK PROTEINS AND NON-MILK PROTEINS BY VARIOUS ENZYMES AT pH 6.1 AND AT THEIR OPTIMUM pH FOR PROTEOLYSIS

	Milk protein[a]		*Non-milk protein*[b]		*Optimum pH*
	at pH 6.1	*at optimum pH*	*at pH 6.1*	*at optimum pH*	*for each enzyme*
Enzyme					
Pepsin	7	74	0	65	2.0
Mucor rennet	14	21	3	5	4.0
Chymosin	13	15	0	0	3.6
Pancreatin	75	77	37	48	8.0
Trypsin	70	69	44	51	8.1
Chymotrypsin	49	54	40	37	7.8
Papain	66	74	58	62	8.0
Pronase	72	79	64	69	7.5

(From Jenkins *et al.*, 1980)
[a]Mean value for skim milk, butter milk and sweet whey powders
[b]Mean value for isolated soyabean protein concentrate, soya protein concentrate, fish protein concentrate and rapeseed protein concentrate

hydrolysed the milk proteins more extensively than they did the non-milk proteins. It would therefore seem that even though the calf can tolerate some of the non-milk proteins, the digestibility of the diet is lower than when milk proteins provide the whole of the protein source.

In addition, when vegetable proteins are used, the carbohydrates are very poorly digested compared to lactose, and often the problems that arise from the use of vegetable proteins are thought to be the result of fermentation of the carbohydrates in the large intestine. It is possible to calculate the digestibility of the carbohydrates of non-milk protein sources, when these are mixed with whey products and a fat source, by assuming

that the digestibility of the carbohydrate in the whey is the same in the diet under test as it is when whey products and the same fat source are used as a control treatment. Such an example is shown in *Table 9.10*, from which it is apparent that the carbohydrates in soya flours are of relatively poor digestibility in the young calf and therefore the maximum level of inclusion is severely restricted during the early stages of the calf's life. With many soya protein sources, replacement of 30% of the protein may be the maximum that can be tolerated.

Table 9.10 APPARENT DIGESTIBILITY OF PROTEIN AND CARBOHYDRATE OF MILK AND NON-MILK INGREDIENTS OF MILK REPLACERS BY CALVES, CALCULATED ON THE BASIS THAT MILK PROTEIN AND CARBOHYDRATE ARE DIGESTED EQUALLY WELL WHEN MIXED WITH A NON-MILK PROTEIN SOURCE AS WHEN COMPRISING THE WHOLE DIETARY SOURCE

	Milk protein	*Soya flour*		*SPC*	*SE*	*Significance*[a]
		High antigen	*Antigen-free*	*Antigen-free*		
DM intake (g/day)	1296	1093	1251	1234	75.1	NS
Weight faeces (g/day)	881	1767	1114	1196	134.1	**
Faecal dry matter (g/day)	113	277	174	188	13.9	***
Intake from total diet (g/day)						
Protein	355	268	317	297	19.4	*
Carbohydrate	555	465	529	534	32.1	NS
Apparent digestibility of total diet						
Protein	0.89	0.54	0.78	0.76	0.031	***
Carbohydrate	0.99	0.91	0.94	0.95	0.011	**
Intake from non-milk source						
Protein	—	166	201	167	12.6	NS
Carbohydrate	—	105	118	52	6.8	***
Apparent digestibility of non-milk source						
Protein	—	0.33	0.72	0.66	0.059	***
Carbohydrate	—	0.64	0.79	0.55	0.069	NS

(Stobo, unpublished)
[a]NS, not significant; $*P<0.05$; $**P<0.01$; $***P<0.001$

The alternative solution to replacing skim milk with non-milk proteins is to replace it with whey products. This would seem to involve less nutritional stress on the calf, since whey is a normal constituent of milk and is highly digestible even though the whey proteins are retained in the abomasum for only a short time. Partial replacement of skim milk is obviously going to affect the ability of the diet to form a firm coagulum in the abomasum (Emmons, Lister and Jones, 1976; Ternouth *et al.*, 1975). Thus it has been argued that if the skim-milk content of the diet is reduced to the extent that rennet coagulation is seriously impaired or even prohibited, complete replacement of skim milk might be preferable (Stobo, 1981). This hypothesis is at present being tested in an experiment in which increasing levels of whey powder and whey protein concentrate are excluded as the skim-milk solids content is reduced from 60% to zero. Preliminary results suggest that the presence of 20% skim milk is not detrimental to the calves even though such a diet does not coagulate with rennet *in vitro*. It is not known whether *in vivo* the whey drains off rapidly and this is followed by coagulation of the casein, or whether the Igs present

in good quality whey proteins play a protective role in the gut; alternatively, possibly the calf can digest uncoagulated skim milk provided it has not received excessive heat treatment. Nevertheless, at the present time it would seem economically desirable to exclude skim-milk powder from milk replacers unless it is included in sufficient quantity to attract the EEC subsidy.

Acidified milk replacers

These products were first developed commercially in the Netherlands where they are now reported to have replaced the more traditional milk replacers for 80% of the rearing as opposed to veal calves. The Dutch acidified milk replacers were based on dried sweet whey from Gouda cheese, whereas many of those manufactured in the UK since 1976 have been based on skim-milk powder. To avoid casein precipitation, the majority of UK products have their pH reduced to only 5.3 to 5.6 and are termed 'medium acid', in comparison with a reduction in pH to 4.4 for the 'high acid' whey-based replacers. A variety of organic acids is used, including citric, malic, sorbic, formic, fumaric and supposedly propionic acid.

The claimed benefits from the use of acidified milk replacers in calf rearing are numerous. Perhaps the greatest advantage is to be found in the preservative nature of the organic acids which therefore allows sufficient milk replacer to be reconstituted to last for up to three days, with consequent increased convenience and reduction in drudgery and labour costs. It is also claimed that acidification prevents the rapid growth of pathogenic organisms in the calf's alimentary tract following an initial digestive upset, and that sucking cold acidified milk from a teat in small quantities at frequent intervals will assist with clotting and aid digestion.

Nutritionally, there appears to be little evidence to substantiate these claims. First, organic acids especially at pH 5 or higher are unlikely to be bactericidal or even bacteriostatic. Second, it has been suggested that when acidified milk replacers are fed, the calf reduces its production of gastric acid to compensate (Webber, Nouri and Bell, 1980) so removing any benefit. Further, once the digesta leave the abomasum, the acids are neutralized with bile and any benefit within the intestine would be questionable.

Nevertheless, a more rapid decline in faecal coliform numbers was recorded when calves were given a 'medium acid' milk replacer without access to dry food until four weeks of age (Simm, Chamberlain and Davies, 1980) or a 'high acid' milk replacer and access to dry food (Humphrey, Kirk and Cooper, 1982). However, no attempt was made to serotype the *E. coli* to find if potentially pathogenic strains were present. In contrast, Kay (1980) found no difference in either *E. coli* or lactobacilli numbers in faeces of calves irrespective of whether they were given acidified or non-acidified milk replacers. However, Kay (1980) also reported that the acidified milk replacer took longer to clot *in vitro*. Morgan-Jones and Hinks (1980) commented that by the time a milk replacer had been reconstituted for three days its bacterial count had risen from 4.8×10^4 to

Table 9.11 EFFECT OF DIET SOURCE, pH AND FEEDING METHOD OF MILK SUBSTITUTES ON NUTRIENT UTILIZATION AT DIFFERENT AGES IN FRIESIAN BULL CALVES

Diet source		Skim based				Whey/fish based			
pH		5.5		6.3		4.3		6.2	
Feeding method		B	T	B	T	B	T	B	T
Dry matter intake	1 week	751	670	848	890	770	744	800	795
(g/day)	4 weeks	935	903	1053	1053	976	839	951	904
	7 weeks	1160	1026	1297	1238	1167	995	1164	1047
Wt faeces DM	1 week	63	50	48	61	63	55	57	66
(g/day)	4 weeks	37	63	34	68	49	79	56	85
	7 weeks	49	67	56	97	65	95	72	99
Apparent digestibility									
Dry matter	1 week	0.92	0.93	0.94	0.93	0.90	0.92	0.93	0.92
	4 weeks	0.96	0.93	0.97	0.93	0.95	0.90	0.94	0.90
	7 weeks	0.96	0.93	0.96	0.92	0.94	0.93	0.94	0.90
Crude protein	1 week	0.88	0.87	0.90	0.88	0.78	0.84	0.85	0.83
	4 weeks	0.94	0.90	0.94	0.91	0.90	0.87	0.89	0.85
	7 weeks	0.93	0.91	0.93	0.89	0.91	0.89	0.90	0.89
ME of diet	1 week	19.2	19.1	19.7	19.2	17.2	17.6	18.5	17.9
(MJ/kg DM)	4 weeks	20.1	18.5	20.3	18.7	18.4	16.7	18.7	16.8
	7 weeks	20.0	17.7	19.9	18.2	18.3	16.7	18.8	16.7

(Stobo, 1981)
B = Bucket T = Teat

3.2×10^7 per ml, which clearly indicated the need for thorough cleaning of equipment if calves were not to be subjected to unnecessary health hazards.

The effects of acidified milk replacers were compared with those of non-acidified replacers based on skim milk or whey supplemented with fish protein, in an experiment in which calves were given the diets by bucket twice daily at 38 °C or with 24-h access by teat at environmental temperature (10–15 °C) (Stobo and Roy, 1980). They found no benefit for the acidified diets and concluded that, provided that calves receive adequate colostrum and the standards of calf management and hygiene are high, there is likely to be little benefit from acidification. This result was substantiated by the findings of Hinks *et al.* (1980) and under more practical conditions by Clench (1981). Stobo and Roy (1980) recorded a high incidence of bloat when the milk replacers were offered cold by teat rather than when given warm by bucket. Subsequently, Stobo (1981) reported that apparent digestibility of the milk replacer diet was reduced at four weeks of age with teat feeding. This added further support to the findings from post-mortem examination of all calves in the experiment that teat feeding was associated with the passage of milk to the rumen, which apart from the bloat hazard was wasteful in dietary energy. As shown in *Table 9.11* the Metabolizable Energy content of acidified milk replacers certainly does not justify a price higher than that charged for a conventional product.

Despite the failure to confirm that acidified milk replacers are beneficial, these products are reported to be gradually replacing the non-acidified products in the UK, but are tending to be fed warm from buckets rather than cold through teats. The rationale for such a change is obscure, but is possibly related to the desire of feedstuffs manufacturers to be seen to be introducing new products and thus score a point at the expense of their competitors in what is a very competitive situation.

Conclusion

Recent technological developments have made available products which economically are more viable than skim-milk powder as the basic ingredient of milk replacers for the calf. Of these, the ability to produce reasonable quantities of antigen-free soya products, following the discovery of the importance of allergies in the calf, and the use of ultrafiltration methods to produce protein-rich and lactose-rich components without denaturing the protein, have offered the most significant opportunities for change.

In the newborn, there is no doubt that the digestive system is suited for the digestion of milk, whereby coagulation of the casein and drainage of the whey permits the initial stages of protein and lipid digestion to occur.

There is little doubt that milk that has received excessive heat treatment and in which the casein will not coagulate satisfactorily is likely to result in the passage of undigested protein into the duodenum and the proliferation of an unfavourable gut flora, followed by diarrhoea. With the recent introduction of non-milk proteins into milk replacers, the views on the

importance of coagulation have been challenged. Nevertheless, it has been shown that digestibility of nitrogen is lower with these milk replacers than with those based on skim milk and therefore the potential risks are greater. Concern has been voiced recently on the growing reliance on the prophylactic use of antibiotics in the diet of various species. It is questionable as to how far the non-milk proteins would be successful for the neonatal calf on a commercial scale in the absence of antibiotics.

Whey proteins as the sole protein source appear to be well tolerated by the young calf and the results of *in vitro* tests suggest that they might prove more suitable for the calf than a mixture of whey proteins with casein.

Although the proportion of acidified milk replacers has tended to increase in recent years, the main advantages appear to be related to the convenience that is associated with a new system of calf rearing. Nutritionally, there has been no proof that acidified products are in any way superior and there can be no substitute for a high standard of management by the calf rearer.

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10

NUTRIENT REQUIREMENT OF THE BREEDING EWE

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Introduction

To provide information on the nutrient requirement of the breeding ewe in such a manner that it can be applied usefully in practice not only involves estimates of needs for maintenance, maternal tissue gain, fetal growth and milk production but also guidance on when and how body tissue can be used safely and efficiently to meet some of the nutrient requirements of pregnancy and lactation. This is one of the reasons why, in the feeding of the breeding ewe, so much importance is attached to the concept of target condition scores at different stages in the reproductive cycle; the others being the direct involvement of body condition on reproductive potential through its effects on ovulation rate and indirectly in late pregnancy via its effects on voluntary food intake.

Targets for body condition

The stylized curves describing changes throughout the year in the live weight and maternal empty body weight of hill ewes (Russel, Gunn and Doney, 1968) provided the initial stimulus for the idea that targets for body condition at each stage of the reproductive cycle were essential in ewe nutrition. Subsequent information on the effects of body condition at mating on ovulation rate and the effects of changes in body condition during pregnancy and lactation on the growth of the products of conception and on milk production form the basis for the changes through the year in body weight and condition that are now recommended in practice (Meat and Livestock Commission, 1981). Briefly these involve having ewes in body condition score 3 to 3.5 at mating (equivalent to approximately 30% fat in the fleece-free empty body; Russel, Doney and Gunn, 1969), falling by not more than 5% in live weight or 0.5 units in body condition in the second and third months of pregnancy, thus avoiding any detrimental effects of undernutrition on the growth of the conceptus (*see Figure 10.1*). Often it is inevitable that ewes will lose some condition in late pregnancy,

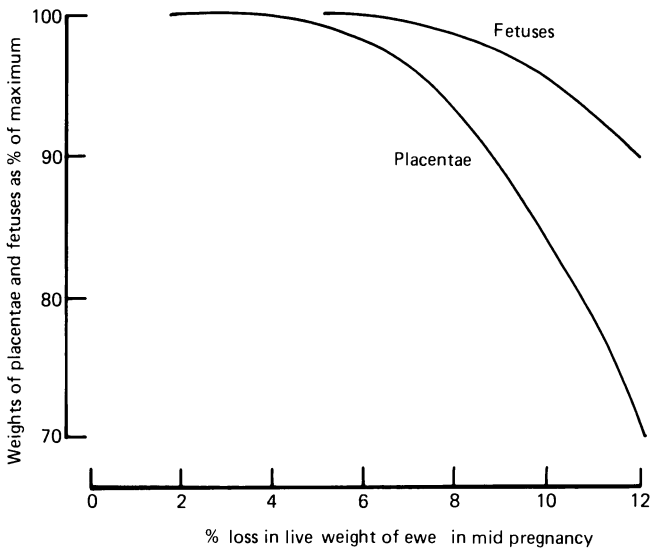

Figure 10.1 The effects of undernutrition during the second and third months of pregnancy on the size of the placentae and fetuses at day 90 of gestation (from data reviewed by Robinson, 1983)

either as a result of an inadequate feed supply in hill and upland flocks or through the inability of highly prolific ewes in lowground flocks to consume sufficient energy to meet the high demands for fetal growth in late pregnancy. Again the recommended guideline is to limit losses in body condition in the last six weeks of pregnancy to 0.5 units. During the first six weeks of lactation losses can be equivalent to as much as 1 unit on the body condition score scale. Therefore from mating to six weeks after lambing, ewes in body score 3.5 can lose up to 1.5 units of condition (equivalent to around 45% of the original fat in their fleece-free empty body). Taking a ewe of 70 kg at mating this means a total loss of approximately 8 kg of fat; equivalent to 314 MJ of energy. Replacing this before rebreeding on forage aftermaths that have a metabolizability of their gross energy (q) of 0.56, which gives rise to an efficiency of utilization of ME for fattening (k_f) of 0.34 (equation 3 page 84, Agricultural Research Council, 1980), requires 925 MJ of ME.

Both the action of replacing body fat prior to rebreeding, which is normally referred to by the industry as 'flushing', and the actual amount replaced, influence the number of eggs that are subsequently shed (Gunn, Doney and Russel, 1969) but the mechanisms whereby body condition and changes in body condition affect ovulation rate are far from clear. Recently, Haresign (1981a) suggested that the 'flushing' effect may operate through a reduction in the atresia of ovarian follicles in the last day or so before ovulation and in another study (Haresign, 1981b), postulated that the low basal levels of luteinizing hormone (LH) that accompany undernutrition may arise from a depression in the activity of the hypothalamic–pituitary axis; for normal levels of pituitary responsiveness to stimulation by luteinizing hormone–releasing hormone (LH–RH) were observed in

undernourished ewes. Support for the hypothesis that undernutrition may influence the release of hypothalamic releasing hormones comes from studies in laboratory animals, in which low food intakes are accompanied by natural decreases in the release of LH, follicle stimulating hormone (FSH), thyroid stimulating hormone (TSH), prolactin and growth hormone from the anterior pituitary (Campbell *et al.*, 1977), but normal levels prevail when exogenous stimulation by LH–RH and thyroid releasing hormone is employed. In the absence of more fundamental knowledge it is a matter of speculation as to whether or not the effects of body condition and level of feeding on ovulation rate, or indeed the effect of correcting a deficiency of a specific dietary nutrient such as protein, which is known to enhance ovulation (Fletcher, 1981), possibly through an increase in plasma FSH concentrations prior to oestrus (Davis *et al.*, 1981), have a common cause, i.e. a reduced ability of the hypothalamus to stimulate the release of gonadotrophins from the anterior pituitary.

Nutrient requirement for early pregnancy

ENERGY

For ewes that are in the correct body condition (3.0 to 3.5, Meat and Livestock Commission, 1981) at mating for maximum ovulation rate, there is now general agreement that maintenance feeding regimens in the first month of gestation are adequate. In a recent review Graham (1982) gives estimates of the daily ME requirements for maintenance of confined sheep of 0.3 to 0.4 MJ/kg $W^{0.75}$ and for those at pasture, 0.4 to 0.8 MJ/kg $W^{0.75}$ depending on feed quality, activity and weather conditions. A recent addition to the environmental factors that influence maintenance energy requirement is a time-of-year effect, directly related to daylength but not necessarily caused by it (Blaxter and Boyne, 1982), and sufficient to alter the fasting metabolism by $\pm 14\%$ of the mean.

As far as the breeding ewe is concerned, maintenance is not simply energy equilibrium but rather the maintenance of body condition and normal rates of wool growth. A daily rate of energy accretion in the fleece of 0.2 MJ is fairly typical for lowground cross-bred ewes in Britain. No absolute estimates for the efficiency of utilization of ME for wool growth are available but recently Graham and Searle (1982) compared the energetic efficiency for the growth of body tissue and fleece in two breeds of sheep differing in their potential for wool production and calculated a marginal efficiency for the utilization of ME for wool growth of 17.5%. Thus the maintenance of normal rates of wool growth could increase the daily ME requirements of the ewe above that required for energy equilibrium by 1.1 MJ or approximately 0.05 MJ/kg $W^{0.75}$. For the major wool producing breeds of the world this estimate could be increased threefold.

PROTEIN

Until about ten years ago protein needs for maintenance were based on nitrogen balance studies; the dietary need being estimated from the

relationship between protein intake and retention and usually taken as the dietary amount that corresponded with either zero protein balance or some positive retention that allowed for normal rates of protein accretion in wool. In recent years research has concentrated on the principles of protein digestion in the ruminant and protein needs have been determined from estimates of the amounts of microbial and undegraded dietary protein together with coefficients for their apparent absorption and subsequent utilization to meet the nitrogen requirement for tissue maintenance, i.e. endogenous urinary nitrogen (Agricultural Research Council, 1980). Based on the results of recent experiments involving the maintenance of ruminants entirely by the intragastric infusion of nutrients it has been shown (Ørskov and MacLeod, 1982) that the tissue maintenance component not only includes endogenous urinary nitrogen but also comprises a considerable proportion of what used to be termed metabolic faecal nitrogen. It has been argued therefore that to increase the tissue maintenance requirement accordingly and use coefficients for true rather than apparent digestion of protein is fundamentally a more correct method of determining protein needs (Ørskov and MacLeod, 1982). Using this approach, i.e. coefficients for true digestibility and subsequent utilization of 0.85 and 0.80 respectively (Storm and Ørskov, 1982) and a net protein requirement for tissue maintenance of 2.2 g/kg $W^{0.75}$ (Ørskov, MacLeod and Grubb, 1980), it can be calculated that at a maintenance energy requirement of 0.42 MJ of ME/kg $W^{0.75}$, a basal diet containing the minimal amount of protein (10 g/MJ of ME) for maximal synthesis of microbial protein would satisfy a net protein need in the ewe of 5.7 g/MJ of ME or 2.4 g/kg $W^{0.75}$ at energy maintenance. This is equivalent to the protein needs for tissue maintenance and wool growth (Robinson, 1983). Bearing in mind that conventional N balance tends to overestimate N

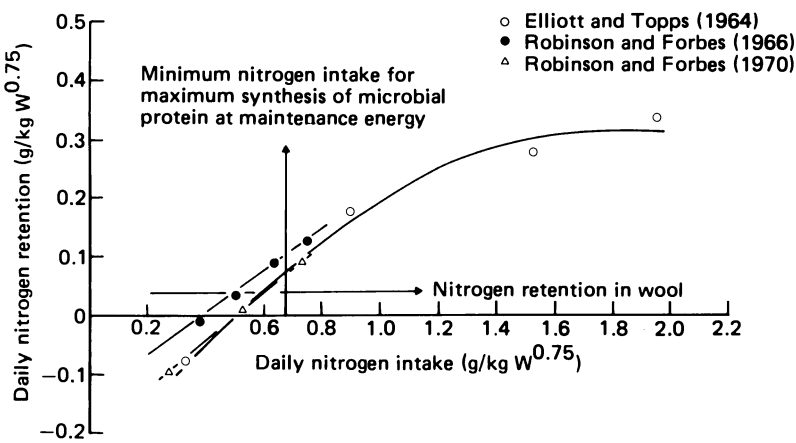

Figure 10.2 Comparison of observations on the overall relationship between nitrogen intake and nitrogen retention with the calculated value for net protein synthesis (intersection of the two 'arrowed' lines) when a basal diet containing 10 g crude protein per MJ of ME is given at energy maintenance. The values used in the calculations of net protein synthesis are those of Ørskov, MacLeod and Grubb (1980) for tissue maintenance and those of Storm and Ørskov (1982) for the true digestibility and subsequent utilization of amino nitrogen (*see text*)

retention, this estimate, which is identified in *Figure 10.2* as the intersection of the two 'arrowed' lines, falls close to the overall relationships between N intake and N retention.

The fact that the sum of the net requirement for protein for tissue maintenance and wool production is similar to the net amount produced from microbial and undegraded dietary protein when a diet containing 10 g crude protein (CP)/MJ of ME is given at maintenance energy, is of practical importance. For ewes kept at maintenance it means that basal feeds which contain less than 10 g CP/MJ of ME should be supplemented with urea in order to ensure maximal synthesis of microbial protein. In most instances sulphur is also required, the appropriate rate of inclusion being 1 part of sulphur for every 13 parts of nitrogen from urea. Care should be taken, particularly in areas of known copper deficiency to avoid an excess of sulphur as this can reduce the availability of copper.

MINERALS AND VITAMINS

It is not intended to detail the mineral and vitamin requirements of the ewe for these have been reviewed by the Agricultural Research Council (1980) and, as far as the minerals and trace elements are concerned, have been updated by Suttle (1983). In addition descriptions of the symptoms of many of the mineral deficiencies and toxicities, together with information on their correction, have been given by Underwood (1977; 1981) and Lee and McIntosh (1982). Rather therefore, it is to draw attention to the fact that although correction of many macro-mineral, trace mineral and vitamin deficiencies improves lambing percentages, it is only in the case of vitamin E and selenium that there is evidence that part of the improvement comes from a reduction in embryo mortality in the third and fourth weeks of pregnancy, i.e. after the start of implantation (*see* review by Robinson, 1983). Prevention of embryo mortality during this period is particularly important for unlike embryo loss prior to implantation which manifests itself solely in reduced lambing percentages, loss during implantation is associated with either delayed returns to oestrus or the birth of smaller lambs than would be expected for their litter size (Rhind, Robinson and McDonald, 1980). Provided there is not a concomitant vitamin E deficiency, selenium deficiency characterized by whole blood selenium concentrations less than 0.05 μg/ml (Anderson, Berrett and Patterson, 1979), can be rectified by supplementing diets that are deficient (i.e. containing < 0.10 mg/kg dry matter; *see* review by Rickaby (1981) for feedstuffs that fall into this category) with 0.1 mg selenium/kg dry matter or by injecting the ewe prior to mating with 5 mg selenium.

Nutrient requirement in mid pregnancy

From the end of the first month to the end of the third month of pregnancy the growth of the fetus in absolute terms is small (*see Figure 10.3*) and places little additional demand on the ewe for nutrients. In contrast, by day 90 the placenta has completed its growth process. No doubt it is this

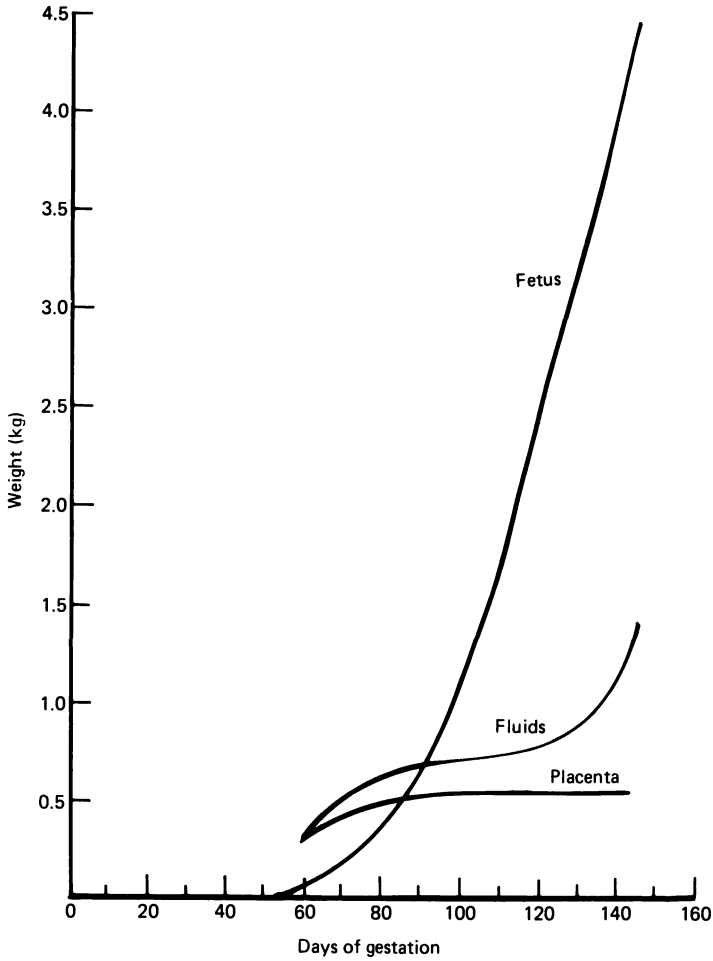

Figure 10.3 The growth of each of twin fetuses and their associated placenta and fluids for a 70 kg ewe at mating (From Robinson, 1982)

difference in growth pattern between the fetus and its placenta that makes the placenta much more vulnerable than the fetus to undernutrition in mid pregnancy (*see Figure 10.1*). Whether or not this reduction in placenta size at day 90 that accompanies losses in ewe body weight that are in excess of 5% in the second and third months of pregnancy (equivalent to energy intakes of 75% of maintenance), is the direct effect of an energy deficit is uncertain. Using the argument advanced earlier (*see* section on protein needs in early pregnancy) that at energy maintenance, microbial and undegraded dietary protein from diets containing 10 g CP/MJ of ME is just sufficient to meet the net protein requirements of the ewe for tissue maintenance and wool production then, it is quite possible that the effects of undernutrition on placental size arise from the failure of the reduced intake of energy to provide adequate microbial protein to meet the net protein requirements for tissue maintenance, wool growth and the normal

development of the conceptus. In this instance it is necessary to provide a dietary protein supplement of low degradability in the rumen.

Nutrient requirement in late pregnancy

ACCRETION OF NUTRIENTS

Division of the rate of accretion of a specific nutrient in the products of conception in late pregnancy by the coefficient for the efficiency of utilization of the dietary nutrient for net accretion, provides an estimate of dietary need. It is this approach that will be used to calculate the nutrient requirement for pregnancy.

Estimates of the average daily rates of accretion of energy and protein in the gravid uterus in late pregnancy and of macrominerals and some trace minerals in the fetuses are given in *Table 10.1*. The data have been

Table 10.1 AVERAGE DAILY RATES OF ACCRETION OF ENERGY AND PROTEIN IN THE GRAVID UTERUS, AND OF MACROMINERALS AND TRACE MINERALS IN THE FETUSES. THE VALUES ARE EXPRESSED PER kg LAMB BIRTHWEIGHT

	Stage of gestation (days)				
	88	*102*	*116*	*130*	*144*
Energy (kJ)	34	54	79	104	128
Protein (g)	1.14	1.79	2.62	3.45	4.27
Calcium (mg)	58	111	169	214	237
Phosphorus (mg)	38	69	96	112	115
Magnesium (mg)	1.86	3.38	4.95	6.14	6.76
Sodium (mg)	16.3	24.3	30.3	33.3	33.3
Potassium (mg)	14.8	22.2	27.6	29.9	29.0
Copper (μg)	16.6	28.5	41.1	52.1	59.4
Zinc (μg)	102.0	160.8	243.6	355.6	501.5
Manganese (μg)	8.4	13.4	15.9	15.3	12.8
Selenium (μg)	0.23	0.34	0.43	0.46	0.43

gathered from a number of sources (Robinson *et al.*, 1977; McDonald *et al.*, 1979; Williams, McDonald and Bremner, 1978; Langlands *et al.*, 1982). For energy, protein, the macrominerals, copper and zinc, the values are means for a range of litter sizes, while for manganese and selenium they are for singles. For ease in application to different ewe breeds and crosses all are expressed/kg lamb birth weight. In addition all estimates of accretion rates were obtained from Gompertz equations of the form

$$\ln w = A - B\exp(-Ct)$$

where w is the weight of the nutrient in the conceptus at time t from conception, and A, B and C are constants obtained by least-square analyses of the data. Differentiating this equation with respect to time gives rates of accretion in the general form $wBC\exp(-Ct)$. It is in this measure, which bears directly on the accuracy of the estimates of nutrient

requirements, that the Gompertz equation is superior to all other equations used to describe prenatal growth data in the sheep (Robinson *et al.*, 1977; Robinson and McDonald, 1979).

EFFICIENCY OF ENERGY UTILIZATION (k_c) FOR CONCEPTUS ENERGY GAIN

Although dietary ME concentration is proportional to metabolizability (q), which is recognized as a major factor determining the efficiency of utilization of ME for maintenance (k_m) and for growth (k_f) of ruminants (Blaxter, 1974), it was not until recently that the suggestion was made that it affects the efficiency for conceptus development (k_c) in a similar way (Robinson *et al.*, 1980). The evidence for an effect is presented in *Figure 10.4*. The open circles refer to those studies in which there was no loss of

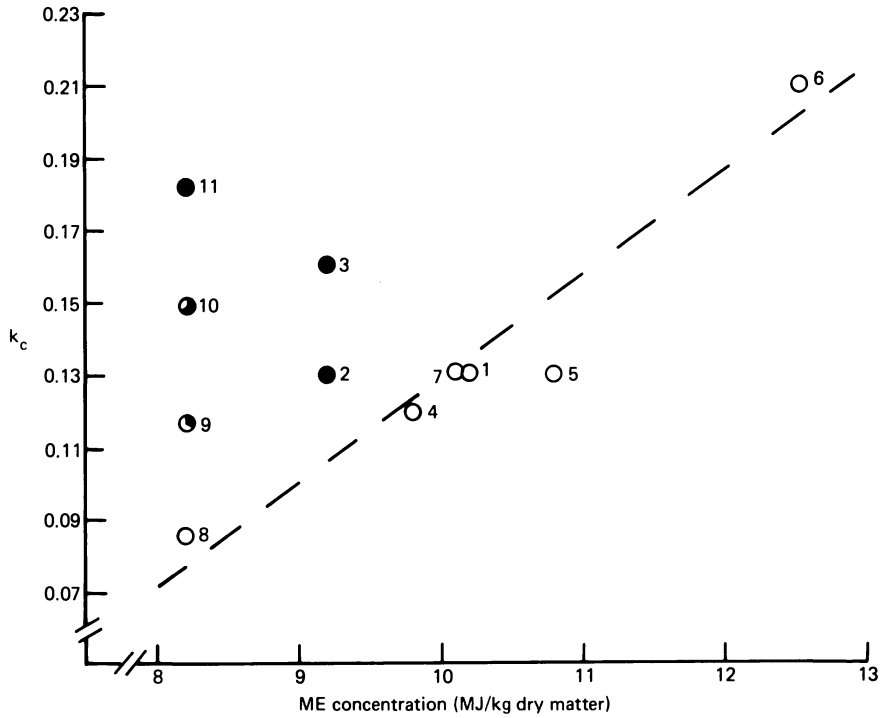

Figure 10.4 Relationship between the ME concentration of the diet and the gross efficiency of energy utilization for conceptus energy gain (k_c). The data sources are (1) Graham, 1964; (2) Sykes and Field, 1972; (3) Lodge and Heaney, 1973; (4,5) Rattray *et al.*, 1973; (6) Heaney and Lodge, 1975; (7) Rattray *et al.*, 1974; (8,9,10,11) Robinson *et al.*, 1980. (From Robinson *et al.*, 1980)

energy from the maternal body, and although not conclusive would appear to justify the tentative hypothesis that ME concentration has a relationship to k_c similar to the accepted relationships to k_m and k_f. The slope of the regression of k_c on ME concentration (MJ/kg dry matter) was 0.029 and for diets with a ME concentration of 10.5 MJ/kg dry matter, which is the concentration normally advocated in practice, there is a cluster of points giving a value for k_c of 0.145.

ENERGY NEEDS

Application of the above coefficient to the rates of energy deposition in the conceptus (*Table 10.1*) gives the estimates shown in *Table 10.2* for the ME requirements above maintenance (ME_P) for fetal growth. For comparison, the likely effects on requirements of using a diet with a lower ME concentration are also given.

Table 10.2 ESTIMATES OF THE DAILY ME REQUIREMENTS (MJ/kg LAMB BIRTHWEIGHT) ABOVE MAINTENANCE (ME_p) FOR CONCEPTUS GROWTH IN RELATION TO STAGE OF GESTATION

ME concentration of diet (MJ/kg dry matter)	*Stage of gestation (days)*				
	88	*102*	*116*	*130*	*144*
	ME_p (MJ/kg lamb birthweight)				
10.5	0.23	0.37	0.54	0.72	0.88
9.0	0.33	0.53	0.77	1.02	1.25

Turning again to *Figure 10.4*, the shaded or partially shaded circles represent data sources in which the energy for conceptus growth was contributed entirely (completely shaded circles) or partially (the shaded portion represents the fraction) by the maternal body. The fact that these points lie above the line suggests that when dietary ME concentration falls below 10 MJ/kg dry matter the energy from maternal tissue is used more efficiently for conceptus gain than that contributed by the diet.

PROTEIN NEEDS

An important outcome of the conclusion (p.147) that at energy maintenance, basal diets containing 10 g CP/MJ of ME, i.e. the minimum for maximal synthesis of microbial protein, just provide enough net protein (5.7 g/MJ of ME) to meet the needs for tissue maintenance, is that immediately the net protein requirement for pregnancy exceeds 5.7 g/MJ of the corresponding ME requirement for pregnancy, a dietary supplement of undegraded protein is needed.

In carrying out the calculations for ewes that are meeting all their energy requirements for conceptus growth from their diet the exercise involves the addition to the net protein accretion in the gravid uterus (*see Table 10.1*), that amount going to the udder and secretions and then expressing the total net protein requirement for pregnancy (NPR_P) in relation to the ME requirements for pregnancy (ME_P, *Table 10.2*). The results of this exercise are illustrated in *Figure 10.5*. Superimposed on the requirement curve is the net protein (5.7 g/MJ of ME) supplied by microbial and undegraded dietary protein when the production component of the basal diet contains 10 g CP/MJ of ME, i.e. the minimum amount for maximal synthesis of microbial protein.

In terms of the nutritional principles involved in feeding the pregnant ewe this exercise is particularly interesting. First of all it means that provided ewes are consuming adequate amounts of energy to meet their needs in late pregnancy then diets containing 10 g CP/MJ of ME would

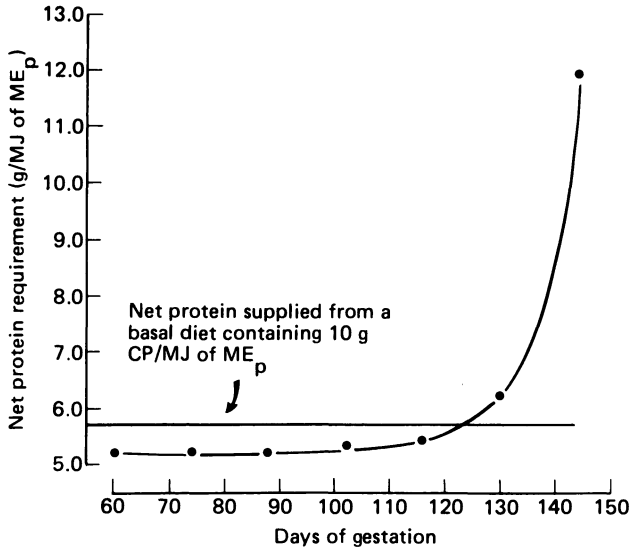

Figure 10.5 The net protein requirement for conceptus growth and udder development (expressed in relation to the ME requirement for pregnancy, ME_p). Superimposed is the net protein supplied by a basal diet containing the minimum amount of protein for maximal synthesis of microbial protein

supply their protein needs up to about three weeks before lambing. Thereafter the rapid increase in the needs of the fetuses together with the growth of the udder and the production of colostrum cause an extremely rapid increase in protein needs to around twice that supplied by the basal diets containing 10 g CP/MJ of ME.

Transforming these values into dietary amounts requires estimates for the efficiency of utilization of microbial and undegraded protein for pregnancy. Although it has been suggested that these may be lower than for normal tissue growth (Robinson, 1982), there are insufficient data to give precise values. If the estimates are indeed lower the error involved in using the existing coefficients for true digestibility and subsequent utilization for growth of 0.85 and 0.80 respectively (Storm and Ørskov, 1982) may be minimal, for in practice they are likely to be balanced by the stimulatory effect of pregnancy on the quantity of non-ammonia nitrogen reaching the abomasum (Thompson, Robinson and McHattie, 1978; Weston, 1979; Faichney and White, 1980).

Using the above coefficients the net requirements for protein are readily transformed into dietary amounts (*see* Robinson, 1983). In practice it is not possible to meet the rapid increase in protein requirements in late pregnancy, which largely arises from the influx of colostrum to the udder. However, since redistribution of body protein in order to ensure adequate udder development and colostrum production occurs in the last few weeks of pregnancy (Robinson *et al.*, 1978), it is more practical to replace the rapid increase (*Figure 10.5*) with a more even pattern. This has been done and the resultant estimates for protein coming from the basal diet and from supplements of undegraded dietary protein are illustrated in *Figure 10.6*

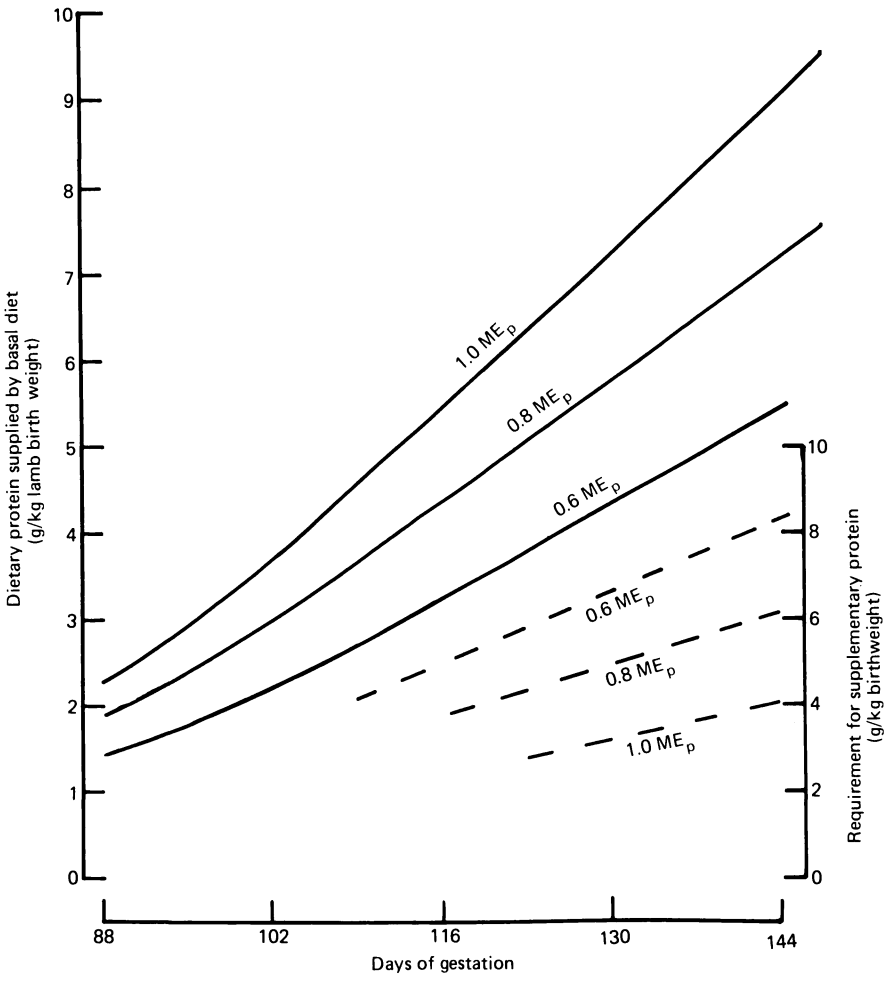

Figure 10.6 The daily amounts of dietary protein supplied by a basal diet containing 10 g CP/MJ of ME_p and given at energy intakes of 1.0 ME_p, 0.8 ME_p and 0.6 ME_p. Also included are the daily requirements for supplementary protein assuming the use of a protein supplement with a degradability coefficient of 0.3. For supplements differing in degradability from the value of 0.3 the amounts are calculated by multiplying the estimates given by the broken lines by the ratio of the degradability coefficients. (From Robinson, 1983)

for ewes receiving all their energy needs from the diet or for those subjected to varying degrees of undernutrition. As illustrated in *Figure 10.6*, when ewes are in energy deficit then the needs for a supplement of dietary protein of low degradability in the rumen occurs much earlier in pregnancy.

It is of interest to compare the requirements in *Figure 10.6*, transformed into amounts of rumen degradable protein (RDP) and undegraded dietary protein (UDP), with those given by the Agricultural Research Council (1980). The comparison is set out in *Table 10.3* for a 75 kg lowground ewe with twin lambs. At all stages the present estimates are higher than those recommended by ARC. That they should be higher is understandable.

Table 10.3 COMPARISON OF THE PRESENT ESTIMATES FOR RUMEN DEGRADABLE PROTEIN (RDP) AND UNDEGRADED DIETARY PROTEIN (UDP) WITH THOSE OF THE AGRICULTURAL RESEARCH COUNCIL (1980) FOR A 75 kg EWE WITH TWIN LAMBS (VALUES ARE IN g/DAY)

		Weeks before lambing			
		6	*4*	*2*	*0*
ARC (1980)	RDP	100	115	140	165
	UDP	—	—	—	10
Present estimates	RDP	108	119	135	150
	UDP	11	14	44	55

Replacement of the old estimate for tissue maintenance based solely on endogenous urinary nitrogen excretion with the higher value which includes a portion of the metabolic faecal nitrogen (Ørskov and MacLeod, 1982), is not completely counterbalanced by the use of true rather than apparent digestibility. As a result some of the UDP (assumed to be 20% for basal feeds), arising as an inevitable consequence of providing the needs of the rumen bacteria for degraded protein, and considered by ARC to be in excess of the needs for tissue maintenance, is in fact now required. The further divergence of the two sets of values in late pregnancy arises from the fact that ARC made no allowance for the additional needs of protein for udder development and colostrum production.

MINERAL NEEDS

In view of the uncertainty which surrounds estimates for the availability coefficients of many of the mineral elements (ARC, 1980), it is not proposed to translate the net accretion rates in pregnancy into dietary amounts. Rather it is to draw attention to the magnitude of the net accretions and their rapid increase in the last six weeks of pregnancy, even when expressed in relation to lamb birth weight (*Table 10.1*). Despite the high rates of accretion of elements such as calcium it is interesting to note that protein undernutrition in late pregnancy caused a much greater reduction in lamb birth weight than the intake of dietary calcium to less than 50% of net accretion rate in the fetus (*see* review by Robinson, 1983).

For the trace minerals, notably copper and selenium, their rates of deposition in the fetus are influenced by the corresponding hepatic and blood concentrations of the ewe (Langlands *et al.*, 1982). For this reason the accretion rates for selenium that are given in *Table 10.1* have been calculated at whole blood selenium concentrations of 0.025 μg/ml, this being the level up to which growth responses in lambs have been noted.

Lactation

For lactating ewes in Britain it is more usual to think of production in terms of lamb growth rate rather than actual milk yield, yet the expression of nutrient requirement is normally in relation to milk production. For ease in transforming milk yields to lamb growth rates during the first three weeks

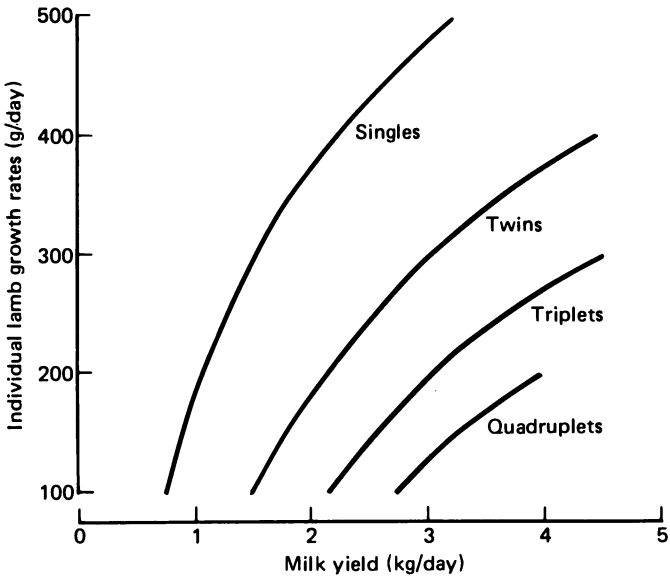

Figure 10.7 Relationship between milk yield and lamb growth rate

of lactation when the lamb is completely dependent on milk, relationships between the two variables are given in *Figure 10.7* for ewes suckling different numbers of lambs. Although the data are from a somewhat empirical relationship (Robinson, Foster and Forbes, 1969) and are extrapolated from singles and twins to include triplets and quadruplets, they do reflect the fact that the efficiency of converting milk to growth is reduced at high milk intakes (Peart, 1982).

MINERAL NEEDS

The outputs (per kg of milk) of the macro and trace minerals are as follows: calcium, 1.9 g; phosphorus, 1.5 g; magnesium, 178 mg; sodium, 0.45 g; potassium, 1.25 g; copper, 0.32 mg; zinc 7.2 mg; manganese, 0.03 mg and selenium 37 μg; the data sources being the Agricultural Research Council (1965; 1980) and for selenium, Gardner and Hogue (1967). Although the availability coefficients for many of these are a matter of conjecture, recommended dietary needs for production (expressed/kg milk) are: calcium, 2.4 g; phosphorus, 2.2 g; magnesium, 1 g; sodium, 0.5 g; potassium, 2 g; copper, 5.3 mg; zinc, 36 mg; manganese, 20 mg and selenium 0.1 mg.

ENERGY AND PROTEIN NEEDS

To transform the net rates of production of energy and protein in milk into dietary needs is a relatively simple exercise. For energy it is a matter of taking calorific values of 4.2, 4.5 and 4.8 MJ/kg for milk with fat contents of

6, 7 and 8% respectively and dividing these by the coefficient for the efficiency (k_l) of utilization of ME for milk production which is 0.63 for a diet with a metabolizability (q) of 0.6 (Agricultural Research Council, 1980). For protein the exercise is very similar to that described earlier for the protein needs of the pregnant ewe. The net synthesis of protein in this instance can be assumed to be 48 g/kg milk, which gives a ratio between the net protein requirement for lactation (NPR_l) and the corresponding ME requirement (ME_l) of 6.7 g CP/MJ of ME_l for ewes producing milk of 7% fat content. Clearly this value lies above the 5.7 g CP/MJ of ME, which is the maximal net synthesis of protein when ewes are meeting all their energy needs for production from diets containing 10 g CP/MJ of ME (*see* section on protein needs in pregnancy). In this instance a dietary supplement of undegraded protein is therefore essential. The actual amount is readily calculated from the factors given in the preceding sections and is 2.1 g/MJ of ME_l for a protein source that has a degradability coefficient in the rumen of 0.3. It is for ewes that fail to meet all their energy needs from the diet, which frequently is the case in practice, that the situation becomes more interesting. For example, if ME_l is only 70% of needs, then the ratio between NPR_l (g) and ME_l (MJ) is 9.6 and the requirement for a supplement of dietary protein with a rumen-degradability coefficient of 0.3 would increase to 8.2 g/MJ of ME, i.e. assuming that body tissue did not contribute to the protein needs for lactation. This assumption is upheld by the results of a comparative slaughter experiment in which lactating ewes were underfed in energy but given a supplementary source of protein of low degradability in the rumen. Between days 12 and 41 of lactation fat loss from the body was 6.9 kg ($P<0.001$) compared with 0.4 kg (NS) for protein

Table 10.4 THE CHEMICAL COMPOSITION OF THE EMPTY BODIES OF LACTATING EWES IN RELATION TO STAGE OF LACTATION

Stage of lactation (days)	*Fat* (kg)	*Protein* (kg)
12	9.2	9.3
41	2.3	8.9
111	1.2	9.2

(From Cowan *et al.*, 1979)

(*see Table 10.4*). In this instance body fat contributed energy for the production of over 50 kg of milk whereas the contribution of body protein to the synthesis of milk protein was unlikely to be more than the equivalent of 6.6 kg of milk.

THE EFFECT OF UNDEGRADED DIETARY PROTEIN ON THE EFFICIENCY OF ENERGY UTILIZATION FOR LACTATION (k_l)

As a result of the observations of Robinson *et al.* (1974) which demonstrated that a supplement of undegraded dietary protein not only enhanced milk yield but was accompanied by an increase in the body weight loss of the ewe (*Table 10.5*), it was generally assumed that the mechanism

Table 10.5 THE EFFECT OF CRUDE PROTEIN INTAKE ON EWE MILK YIELD AND EWE BODY WEIGHT CHANGE IN EARLY LACTATION

CP in diet (%)	10.3	13.6	16.9
CP intake (g/day)	273	340	415
CP (g) to ME (MJ) ratio	11.1	13.8	16.0
Milk production (kg/day)	2.42	2.93	3.10
Ewe weight change (g/day)	-118	-170	-265

(From Robinson *et al.*, 1974)

whereby dietary protein increased milk production centred on its stimulatory effect on the amount of body fat used for milk synthesis. More recent studies involving comparative slaughter do not support this view (Cowan *et al.*, 1979; 1980; 1981). Rather they indicate that the major determinants of body fat loss in the lactating ewe are the amount of fat in the body and the level of ME intake (*see Figure 10.8*). Where undegraded dietary protein appears to exercise its effect is in an enhanced efficiency of energy utilization for milk synthesis (k_l) as illustrated in *Figure 10.9*. The other interesting feature of the data presented in *Figure 10.9* is that the diet with the higher concentration of protein resulted in a higher and later peak yield of milk protein and a more persistent lactation.

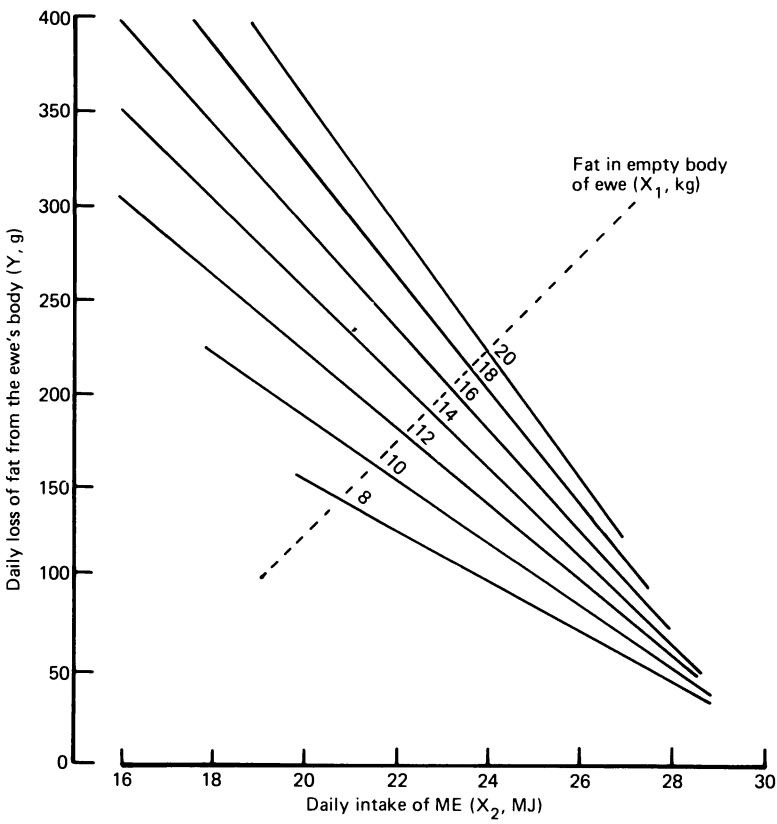

Figure 10.8 The effect in lactating ewes of energy intake and the amount of fat in their bodies on the rate of fat loss. Taken from the relationship $Y = (51 - 1.7X_2)X_1 + 19$ (Residual SD = 20) (From Cowan *et al.*, 1982)

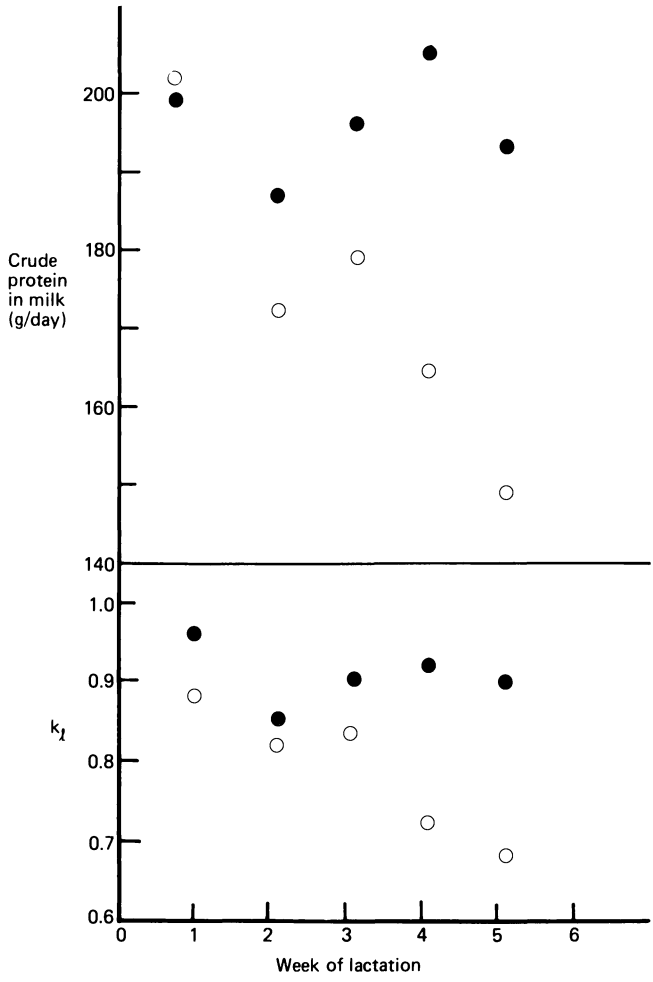

Figure 10.9 Crude protein output in milk and the energetic efficiency of milk synthesis (k_l) for ewes given diets containing either 116 g CP/kg dry matter, ○ or 143 g CP/kg dry matter, ● (From Cowan *et al.*, 1981)

RESPONSES TO DIFFERENT PROTEIN SUPPLEMENTS

An example of the effects on milk yield of supplementing a basal diet of hay and barley with different protein sources is given in *Figure 10.10*. The coefficient for the degradability of the protein from each source in the rumen is given alongside the response curves for milk production and the inverse relationship between the two measures is clearly apparent. In this study the overall relationships across the protein sources, between the non-ammonia nitrogen (x, g/day) reaching the abomasum and the true-protein nitrogen in milk (y, g/day) was $y = 0.58x - 4.9$ ($r = 0.87$). This does not mean however that responses in milk yield are solely due to the quantity of undegraded protein reaching the abomasum. Quality, in terms

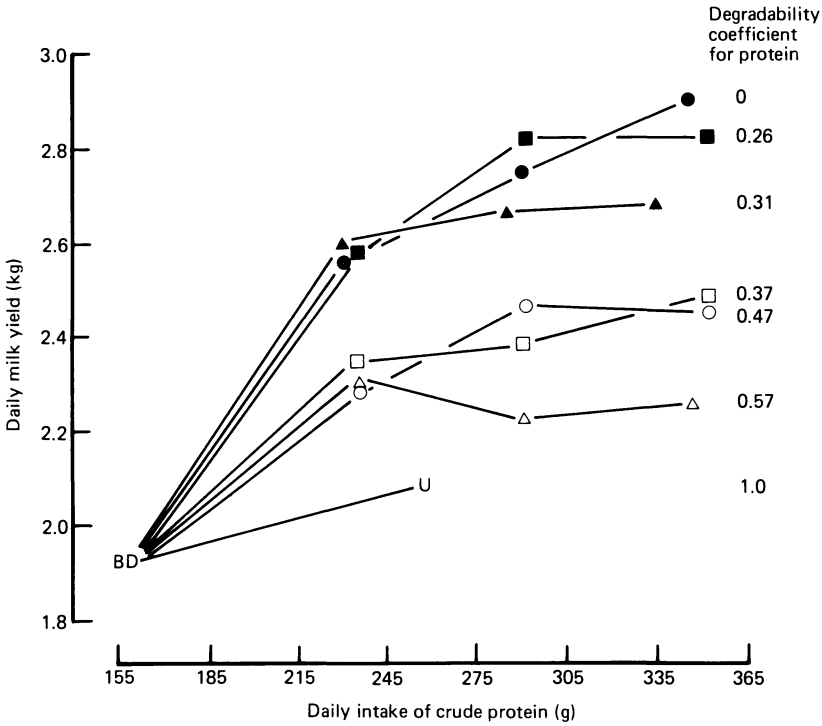

Figure 10.10 The effect of supplementing a basal diet (BD) of hay and barley with either urea (U); ground nut meal (△); soya bean meal (○); meat and bone meal (□); linseed meal (▲); fish meal (■); or blood meal (●), together with the degradability coefficient for each protein source (From Gonzalez *et al.*, 1979; 1982)

of amino acid composition, is likely to play a part. In this context it is of interest to note that Barry (1981) found an enhanced net synthesis of protein in growing lambs on fresh herbage supplemented with abomasal infusions of casein and methionine.

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11

GROWTH PROMOTERS AND THEIR IMPORTANCE IN RUMINANT LIVESTOCK PRODUCTION

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Introduction

Growth promoters are substances that are either added to a nutritionally adequate and balanced diet or are directly introduced into body tissue of healthy animals to induce improvements in feed conversion efficiency. The first of these two groups are essentially growth promoting feed additives, and act within the digestive tract. It is this group of feed additives which will be considered in this chapter. The second group comprise the anabolics which in general are implanted directly into body tissues; however, in the early days some forms of these anabolics were added to the feed and achieved their effect after absorption from the digestive tract. This chapter will make no attempt to discuss the anabolics whether given orally or as is normal today, by implant.

In ruminant and non-ruminant livestock production the majority of the growth promoting feed additives available in the market are antibiotics. It is appropriate to begin by placing the current upsurge of interest in this topic in its historical context. In 1953, the Therapeutic Substances Act became effective. The act provided that the general prohibition imposed by the 1947 Penicillin Act on the supply of specified antibiotics should not apply to the sale of antibiotics for use as growth promoters in animal feeds. Consequently, the 1950s and 1960s were a period when usage of antibiotics as feed additives expanded enormously, and not only in this country; *Table 11.1* shows the quantities (kg $\times 10^6$) of antibiotics produced in the USA from 1951 to 1978. It is apparent that the proportion of the total production that derives from the feed additive market has increased very considerably. It has been estimated (Armstrong, 1981) that in 1981 the value of the world feed additive market was $\$1.69 \times 10^9$ of which 27%, that is $\$0.46 \times 10^9$, was growth promoters. Market projections indicate that in 1990 the world antibiotic market will be worth $\$2.5 \times 10^9$ of which 45–55%, that is $\$1.13–1.38 \times 10^9$, will be antibiotics used as feed additives. The expansion of the market has not only been through greater usage by pig and broiler producers, but, particularly since the late 1960s, through an extension of usage to other forms of production, eggs, veal and beef.

Table 11.1 ANTIBIOTIC PRODUCTION (kg × 10^6) FROM 1951–1978 IN USA

Year	*Total*	*Medicinal use*	*Feed additives (+ other uses)*	*Feed additives as a proportion of total (%)*
1951	0.69	0.58	0.11	15.9
1956	1.24	0.89	0.35	28.2
1961	2.31	1.50	0.82	35.5
1966	4.40	2.45	1.91	43.4
1971	8.12	4.90	3.22	39.7
1976	9.30	4.72	4.54	48.8
1978	11.66	6.08	5.58	47.9

From Savage (1980)

However, concurrent with this expansion, there has been an increasing awareness of, and concern about, the implications of feeding sub-therapeutic doses of antibiotics for growth promotion that were also used therapeutically in farm animals and man. The recommendations of the Swann Report (1968) were essentially designed to alleviate this concern, and in the UK from 1971 onwards therapeutic antibiotics could only be used in feeds under veterinary prescription. Hence for antibiotics to be included in feeds without prescription, they were required to have no therapeutic potential and evidence was needed that resistance transfer from non-pathogenic to pathogenic bacteria was unlikely. It has been estimated (Braude, 1978) that in 1970 those antibiotics of no therapeutic value accounted for less than half of the total antibiotics used as feed additives, whereas in 1975 the situation had reversed.

During the period 1950–1970, knowledge of ruminant digestive physiology had also vastly expanded and it became apparent that the original assumption, embodied in the regulations of the 1953 Act, that oral administration of antibiotics would be to the detriment of the symbiotic relationship that exists between the rumen microflora and its host, such that the nutrient supply to the host would be rendered inadequate, was exaggerated. Indeed, it was realized that carefully controlled administration of certain antibiotics may even be of benefit to the ruminant animal, a realization epitomized by the discovery that inclusion of the antibiotic monensin-sodium in the diets of meat producing ruminants increased the efficiency of food conversion into meat.

The purpose of this chapter is to try and define more precisely the potential of growth promoting feed additives in ruminants. To this end three questions can be posed:

(1) Can areas of inefficiency in the digestive processes of the ruminant be defined so that specific targets for growth promoting agents can be singled out?
(2) What is the efficacy of the growth promoting feed additives currently being tested or used in ruminants and how do these data relate to systems of livestock production used?
(3) How and where do these additives act in the digestive tract and can the observed improvements in animal performance be explained solely through improvements in efficiency of digestion?

These three questions will now be considered separately and in detail.

Efficiency of digestion in the rumen

The ruminant animal is supplied with a large proportion of its energy requirements in the form of volatile fatty acids (VFA) derived from the fermentation of carbohydrate in the rumen. To maximize the energy input into the animal the fermentation of carbohydrate in the rumen must be as efficient as possible. There are two interrelated means by which this can be achieved. The first is the inhibition of rumen methanogenesis. It has been estimated that between 6–10% of the daily gross energy (GE) intake from feed is lost as methane when animals are fed at maintenance, and that above maintenance the loss is related to the GE intake, the level of feeding and the digestibility of the feed (Blaxter and Clapperton, 1965). However, reducing methane production is only of consequence if the energy (metabolic hydrogen) thus spared is diverted into synthesis of other useful products through such processes as hydrogenation of unsaturated fatty acids, the microbial synthesis of lipid and protein, and especially the production of propionate. Secondly, the proportion of feed energy that is captured in the VFAs produced by fermentation depends on the relative production rates of the major VFAs. The efficiencies (%) of capture of hexose energy in the major VFAs are 62.5, 109.2 and 78.0 for acetate, propionate and butyrate respectively. Hence, a fermentation favouring the production of propionate results in a more efficient capture of hexose energy in useful end products (Hungate, 1966). Clearly, since the production of propionate involves utilization of metabolic hydrogen, the inhibition of methane and the enhancement of propionate production are intimately related; however, in relation to the control of rumen fermentation it is useful to consider the two processes as separate targets.

The nitrogen (N) economy of the ruminant animal is largely governed by the quantity and quality of the protein entering the small intestine; this is dependent on the extent of microbial protein synthesis in the rumen and the extent to which a particular protein source passes through the rumen intact. Provided that firstly, the feed protein is of good quality, secondly, that sufficient degradation of protein entering the rumen occurs to supply the microbial biomass with its requirement for preformed amino acids, and thirdly, that there is sufficient non-protein N in the diet to supplement the endogenous supply of N in the saliva, such that microbial protein synthesis from ammonia can continue, then increasing the quantities of feed protein escaping degradation in the rumen is liable to enhance the overall N economy of the animal.

The efficacy of antimicrobial feed additives with particular reference to beef production

From the viewpoint of the producer, the efficacy of a growth promoting feed additive is dependent on an observable improvement in the profitability of his enterprise; an improvement most obviously seen when treated stock retain or improve condition and gain weight more rapidly. However, weight gain is not the only guideline to profitability and improvements can equally well be achieved through reductions in feed intake/unit weight gain. Indeed, the primary purpose of a growth promoting feed additive is

to improve the efficiency of feed conversion into meat either through a reduction in feed intake with maintenance of growth rate, or through the maintenance of feed intake with an enhancement of growth rate or finally, as occurs most often in practice, through a combination of both processes. The efficacy of a growth promoting feed additive for an individual producer will also depend on its applicability to his particular production system.

In a widely diversified beef market such as exists in Europe, an 'ideal' growth promoting feed additive must have 'adaptability', wherein improvements in feed conversion efficiency (FCE) can be achieved in widely differing production systems. This may well mean the utilization of different modes of administration of the additive (e.g. in complete feeds, in supplements, as a rumen bolus or incorporation into mineral licks) together with a range of efficacious doses such that precision of input is not a vital criterion of economic effectiveness. The efficacy of two products, Romensin (monensin-sodium) and Avotan (avoparcin) will now be considered in relation to their influence on FCE. The first of these two examples is chosen because it is the most important product currently available for beef cattle, and the second as an example of a product now under test, and for which beneficial effects have been substantiated.

The initial work on monensin in beef animals was carried out in the feedlot systems of the USA. When added to feedlot rations of high energy density, monensin improved FCE by 5–15%; an improvement achieved through a reduction in feed intake and the maintenance of unchanged growth rates (Raun *et al.*, 1976; Perry, Beeson and Mohler, 1976; Utley *et al.*, 1976). In contrast, when high forage diets (low energy density) were provided the rate of weight gain was significantly enhanced by 25% while feed intake remained unchanged (Dinius *et al.*, 1978). However, steers fed maize silage *ad libitum* with a small soya bean meal supplement exhibited no response in growth rate, but intake was significantly depressed by 6% (Byers, 1980). In another experiment, also using steers fed maize silage *ad libitum*, improvements in weight gain and a reduction in feed intake were recorded (Steen *et al.*, 1978).

An explanation of this variability in response has been put forward (Potter *et al.*, 1976). When fed high energy density rations or exceptionally good quality forages, the animal is already receiving a maximal Net Energy (NE) load and hence NE input, rather than gut fill or rumen distension, is governing control of feed intake. Thus if monensin increases the supply of NE/unit feed consumed then this would result in a reduction in feed intake.

The response of beef cattle to monensin under European conditions is shown in *Table 11.2*, which summarizes data from 35 trials carried out in a number of different types of production system, using different diets and different dose rates (Hawkridge, 1980). It can be seen that FCE was improved by between 6.5 and 10.3%. The response in growth rate (average daily gain, ADG) was similar at all dose rates, but the reduction in feed intake gradually increased as dose rate increased. In a further analysis of the data (*Table 11.3*) the response to monensin in maize silage systems was compared with that in barley beef systems. It is evident that although the response in FCE was similar (–8.3 v. –9.7%), the main component in the improvement in barley beef systems was enhancement of growth rate

Table 11.2 ADJUSTED TREATMENT MEANS FOR POOLED TREATMENT CLASSES FOR 34 TRIALS CARRIED OUT IN EUROPE IN WHICH MONENSIN WAS USED AS A FEED ADDITIVE FOR BEEF CATTLE. VALUES IN PARENTHESIS ARE PERCENTAGE CHANGES FROM CONTROL

Monensin (ppm)	*No. of replicates*	*Average daily gain* (kg)	*Average daily feed intake* (kg)	*Feed conversion efficiency*
0	94	1.153	7.45	6.59
10–13	11	1.206 (4.60)	7.28 (–2.28)	6.16 (–6.53)
16–21	14	1.196 (3.73)	7.19 (–3.76)	6.05 (–8.19)
25–33	77	1.213 (5.20)	7.15 (–4.03)	6.02 (–8.65)
37–40	16	1.208 (4.71)	6.95 (–6.71)	5.91 (–10.32)

(From Hawkridge, 1980)

Table 11.3 ADJUSTED TREATMENT MEANS FOR BEEF CATTLE GROWTH PERFORMANCE WHEN MONENSIN WAS USED AS A FEED ADDITIVE IN 12 TRIALS WHERE MAIZE SILAGE WAS FED AND IN EIGHT TRIALS WHERE BARLEY CONCENTRATE WAS FED. VALUES IN PARENTHESIS ARE PERCENTAGE CHANGES FROM CONTROL

Type of ration	*Monensin* (ppm)	*No. of replicates*	*Average daily gain* (kg)	*Average daily feed intake* (kg)	*Feed conversion efficiency*
Maize–	0	43	1.218	7.44	6.18
silage	30	46	1.275 (4.7)	7.14 (–4.6)	5.67 (–8.3)
Barley–	0	19	1.205	7.27	6.07
concentrate	30/40	24	1.295 (7.5)	7.07 (–2.8)	5.48 (–9.7)

(From Hawkridge, 1980)

Table 11.4 OVERALL SUMMARY OF 30 TRIALS ON HOUSED OR FEEDLOT CATTLE, SHOWING THE AVERAGE PERCENTAGE EFFECTS DERIVED FROM AVOPARCIN IN GROWING-FINISHING CATTLE

	Avoparcin (ppm)			
	15	*30*	*45*	*60*
Trial length: 84 days				
Average daily gain	5.4	5.6	6.4	4.3
Average daily feed intake	–0.5	–2.3	–5.7	–4.1
Feed conversion efficiency	–4.7	–6.4	–9.9	–11.2
Trial length: 112 days				
Average daily gain	2.7	4.3	1.6	3.9
Average daily feed intake	–0.6	–2.5	–6.0	–3.6
Feed conversion efficiency	–3.2	–6.6	–7.5	–6.9
Trial length: 130 days +				
Average daily gain	5.4	2.7	3.7	4.9
Average daily feed intake	–3.4	–2.6	–5.2	–3.7
Feed conversion efficiency	–10.6	–5.0	–8.9	–8.0

(From Mudd and Smith, 1982)

whereas in the maize silage systems the contributions of enhanced growth rate and reduced intake were approximately equal.

Responses to avoparcin inclusion in beef cattle rations are less well documented since it is only recently (Johnson *et al.*, 1979; Delay, Zimmer and Simkins, 1978) that interest in the use of avoparcin has blossomed. *Table 11.4* summarizes data relating to the response of growing-finishing housed or feedlot cattle to avoparcin in 30 trials (Mudd and Smith, 1982).

Improvements in FCE due to avoparcin varied between 3.2 and 11.2% depending on age of the animals and dose rate. The data tend to suggest an inverse relationship between dose level and the age of the animal, low dose rates (15 ppm) achieving greater responses in older animals. These data indicate a considerable potential for avoparcin and collection of further data, especially relating to responses in different production systems will particularize the extent of that potential.

The major obstacle to the use of growth promoting feed additives in grazing animals is clearly one of method of administration. For the purpose of assessment small supplements containing the product to be tested can be supplied, but it should be pointed out that this procedure may have limited relevance in practice. Alternatively, the animals can receive the product by its incorporation into mineral licks or they can be dosed with a rumen bolus designed to release the drug into the rumen over an extended period of time.

In the USA, the effect of feeding supplements containing monensin to grazing cattle was to improve growth rate (Potter *et al.*, 1976). In 12 trials carried out in Europe, the mean improvement in growth rate when monensin was added to a supplement to provide 200 mg monensin/head/day was 13.7% (Wilkinson *et al.*, 1980). The inclusion of avoparcin at 400 or 500 mg/head/day in supplements to grazing cattle improved daily liveweight gain by 9.6 and 11.6% respectively. Of particular interest from the practical viewpoint, is data showing that inclusion of avoparcin in mineral licks (*see Table 11.5*) resulted in very marked improvements in

Table 11.5 THE EFFECT OF AVOPARCIN INCLUSION IN MINERAL LICKS ON GROWTH PERFORMANCE, EXPRESSED AS PERCENTAGE CHANGE FROM CONTROL, IN TWO TRIALS USING GRAZING GROWING-FINISHING CATTLE

	Avoparcin (mg/head/day)			
	0	*100*	*200*	*400*
Trial 1				
Average daily gain (kg)	0.494	—	—	—
Average daily gain (% change)	—	20.6	43.9	11.5
Trial 2				
Average daily gain (kg)	0.644	—	—	—
Average daily gain (% change)	—	31.7	30.9	29.0

(From Mudd and Smith, 1982)

growth rate; at a dose rate of 200 mg/head/day avoparcin induced improvements in growth rate of 30.9 to 43.9% (Mudd and Smith, 1982). The responses to avoparcin appeared greatest when growth rates were low, presumably a reflection of the quality of the pasture. It would be of interest to know something of the behaviour of the cattle in relation to these mineral licks, and how the dose rates for avoparcin intake were calculated.

Mode of action of growth promoting feed additives in ruminants

The effectiveness of two growth promoting feed additives in a wide range of production systems has been demonstrated, but it is important to

determine the nature of these improvements. To know how and where growth promoting feed additives induce the responses in FCE is important because it may allow a more effective use of the additives and indeed extend their use to spheres not originally envisaged (e.g. the dairy cow). To do this it is useful to sub-divide the additives into those whose action is primarily chemical and those whose action is antimicrobial. Examples of the former are methane or deaminase inhibitors. Of the latter, in addition to monensin and avoparcin, virginiamycin (Parigi-Bini, 1979), flavomycin (Zotovic, 1978; Milosevic, Romcevic and Milosevic, 1981), salinomycin (Harenza *et al.*, 1979) and lasalocid (Bartley *et al.*, 1979; Berger, Ricke and Fahey, 1981) are further examples of antimicrobials that exhibit growth promoting properties when fed to ruminants. Collectively all of these agents, chemical and antimicrobial, tend to be referred to as 'rumen modifiers' since their primary site of action in the digestive tract is the rumen. Some detail relating to chemical additives and their effects in the ruminant digestive tract will be given, but it should be stressed that little use has yet been found for these products in practice.

CHEMICAL CONTROL OF METHANOGENESIS AND PROTEIN DEGRADATION IN THE RUMEN

The benefits to be derived from inhibition of methanogenesis have already been outlined. Numerous chemicals have been tested for this property. Unsaturated fatty acids have been shown to inhibit methane production *in vitro* and *in vivo* (Czerkawski, Blaxter and Wainman, 1966; Demeyer and Henderickx, 1967; Clapperton and Czerkawski, 1969). The mechanism of action appears complex; inhibition arises partly because unsaturated fatty acids act as competitors for metabolic hydrogen, and also because they have a direct toxic effect on methanogenic bacteria (Demeyer and Henderickx, 1967). However, reductions in overall fermentation rate, and hence production of VFAs, have also been attributed to unsaturated fatty acids (Marty and Demeyer, 1973). Halogenated methane analogues such as chloroform, carbon tetrachloride and methylene chloride have been shown to inhibit methane production almost completely (Chalupa, 1980), an inhibition associated with an accumulation of hydrogen gas, but also some evidence of enhanced propionate production (Bauchop, 1976).

At least two major problems arise when methane inhibitors are used in animals. Firstly, compounds such as chloroform are volatile and hence unsuitable as feed additives. Furthermore, the palatability of the ration can be affected; rations laced with chloroform proved somewhat unappetizing (Basemaeil and Clapperton, 1973). Closely related, but less volatile chemicals, such as chloral hydrate and the hemiacetyl of chloral and starch (HCS) have been shown to inhibit methane production (Marty and Demeyer, 1973). However, a second major problem which also applies to these chemicals is that of adaptation of the rumen microbial biomass to the presence of the chemical (Chalupa, 1980), an occurrence seen with a number of products tested in the laboratories at Newcastle. When a sheep was fed a diet containing 150 ppm of a compound exhibiting methane inhibiting properties for a period of 59 days, major beneficial changes in

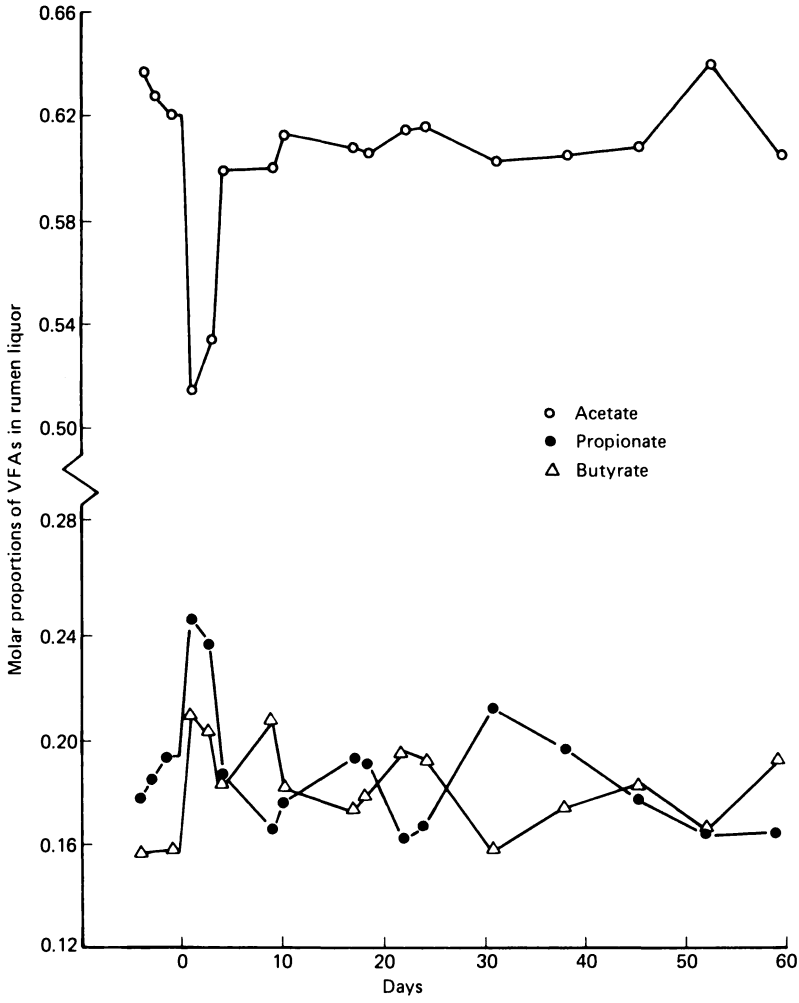

Figure 11.1 The molar proportions of the VFAs, acetate, propionate and butyrate, in the rumen liquor sampled from a sheep at regular intervals throughout the control period (up to day 0) and the treatment period, in which 150 ppm of a methane inhibitor was fed (from Allen, 1981)

the molar proportion of VFAs in rumen fluid (see *Figure 11.1*) had disappeared after approximately ten days (Allen, 1981). *In vitro* estimations of methane inhibition confirmed that initially very high levels of inhibition had also dissipated within ten days.

With reference to control of protein degradation in the rumen, it should be pointed out that the majority of work carried out in this field has related to pretreatment of protein sources in order to protect them from rumen degradation. However, some attempts to control this process by feed additives have been made. For example, diaryliodium chemicals are deaminase inhibitors, and one such compound has been shown to improve the N economy and performance of ruminant livestock (Chalupa, 1980).

Little commercial exploitation of these chemical rumen modifiers has been possible. Indeed until some of the problems noted have been overcome, the potential of these products in practice must remain somewhat bleak. However, it should be noted that cases of enhanced animal performance have been observed; for example, HCS increased overall FCE in lambs over a 90-day feeding trial (Trei, Scott and Parish, 1972).

ANTIMICROBIAL AGENTS

Monensin (Richardson *et al.*, 1976; Van Nevel and Demeyer, 1977; Daenicke, Rohr and Oslage, 1981; Dinius *et al.*, 1978) and avoparcin (Ingle, Dalrymple and Kierman, 1978; Froetschel *et al.*, 1981; Chalupa *et al.*, 1981; Macgregor and Armstrong, 1982) and other products such as flavomycin and selenomycin (Cafantaris, 1981) have all been shown to induce a shift in the pattern of rumen fermentation in favour of propionate. Associated changes accompanying propionate enhancement vary with the product and with dietary and other factors. The mode of action of two such products, monensin and avoparcin, will now be examined in some detail.

Monensin belongs to class of compounds referred to as monocarboxylic ionophores (Gorman, Chamberlin and Hamill, 1967) and is produced by a strain of *Streptomyces cinnomonensis*. Since it is an ionophore, it has the property of rendering cations lipid-soluble by binding them within its lipophilic structure (Pressman, 1976). Monensin has an especial affinity for sodium such that it has the ability to facilitate the entry of sodium into the bacterial cell so causing disruption to the internal ionic environment (Austic and Smith, 1980). Gram-positive bacteria are more susceptible than Gram-negative bacteria (Haney and Hoehn, 1967). When present in the rumen, it is considered that monensin enhances the supply of substrate for the monensin-resistant species of succinate and propionate producing bacteria, and reduces that for methanogenic bacteria by inhibition of those species of bacteria producing acetate, butyrate, formate and hydrogen (Chen and Wolin, 1979). Methane production can be reduced by 20–40% *in vitro* (Allen, 1981).

It is of interest that monensin enhanced propionate production by 76% when added to a high concentrate diet, but by only 56% when added to a high forage diet (Van Maanen *et al.*, 1978), although questions about the validity of the marker used to measure propionate production in the study have been raised (Rowe and Broome, 1981). In both high forage and high concentrate feeding regimens, the metabolizable energy (ME) supply/unit feed intake will be increased because of a more efficient transfer of feed energy into useful product; indeed Rowe, Davies and Broome (1982) showed that 20% more ME was available from rumen fermentation when monensin was fed in the diet. In a continuous fermentation system, monensin induced a greater response in propionate production when the dilution rate was low (Stainer and Davies, 1981). Monensin can also induce reductions in rumen fluid dilution rate *in vivo* (Allen and Harrison, 1979).

In the last mentioned study, the organic matter digested in the rumen was increased, while the efficiency of microbial protein synthesis was reduced, as was the degradation of feed protein in the rumen when

monensin was present in the diet. Further evidence (Poos, Hanson and Klopfenstein, 1979; Whetstone, Davis and Bryant, 1981) support the hypothesis that part of the explanation for enhanced FCE deriving from the feeding of monensin is due to an increased supply of amino acids to body tissue, resulting from increased quantities of feed protein escaping degradation in the rumen. It follows that under dietary conditions where the feed protein supply is poor either in quantity or quality, or secondly, when the feed N is mainly in the form of non-protein N, then the benefits of monensin feeding are likely to be less evident. Indeed decreases in animal performance have been recorded when monensin was added to a diet in which a large proportion of the feed N was in the form of urea (Oltjen, Dinius and Goering, 1977). It is not entirely clear whether rumen proteolysis or deamination or both are inhibited by monensin; in one *in vitro* experiment, monensin resulted in an increase in proteolytic activity, but more protein escaped degradation (Wallace, Czerkawski and Breckenridge, 1981).

Since monensin is a coccidiostat, reductions in rumen protozoal numbers could theoretically occur, an effect which would reduce N recycling in the rumen. However, the published data are not consistent; monensin either did (Journey and Sewaud, 1978; Oddy *et al.*, 1978) or did not (Dinius and Simpson, 1975; Dinius, Simpson and Marsh, 1976) affect protozoal numbers.

Finally, it should be noted that aversion to diets containing monensin has been observed (Baile *et al.*, 1979), especially when included in concentrate diets. Such an effect is presumably entirely independent of the antimicrobial properties of monensin. How important a contribution this aversion makes to the reduction in feed intake warrants investigation. The effects of monensin on FCE can in the main be attributed to a combination of the

Table 11.6 THE EFFECT OF INCREASING CONCENTRATIONS OF AVOPARCIN AND MONENSIN IN THE MEDIUM ON THE MOLAR PROPORTIONS OF VFAs, TOTAL VFA CONCENTRATION, AND METHANE INHIBITION IN AN *IN VITRO* FERMENTATION SYSTEM IN WHICH RUMEN FLUID TAKEN FROM UNADAPTED SHEEP WAS INCUBATED FOR 22 h. THE SHEEP RECEIVED A RATION COMPRISING 50% BARLEY WHEN MONENSIN WAS TESTED BUT ONLY 30% WHEN AVOPARCIN WAS TESTED

	Antibiotic (ppm in incubation medium)			
	0	*2*	*8*	*20*
Monensin				
Molar proportions of C_2	0.533	0.515	0.510	0.501
C_3	0.213^{a}	0.231^{ab}	0.248^{b}	0.243^{b}
C_4	0.206	0.219	0.201	0.219
Total conc. VFAs (mm/ℓ)	99.0	88.0	80.0	92.0
Inhibition of methane (%)	—	9.8	16.5	18.2
Avoparcin				
Molar proportions of C_2	0.644	0.633	0.622	0.617
C_3	0.177^{a}	0.185^{ab}	0.197^{b}	0.199^{b}
C_4	0.142	0.147	0.144	0.147
Total conc. VFAs (mm/ℓ)	91.7^{ab}	99.8^{a}	84.6^{ab}	80.7^{c}
Inhibition of methane (%)	$—^{a}$	7.2^{a}	16.4^{b}	22.5^{c}

(Unpublished data of R.C. Macgregor and J.D. Allen).

[a,b,c]Values in the same row with different superscripts are significantly different ($P<0.05$)

energetic advantages of a high propionate fermentation associated with a reduced energy loss as methane, together with an enhanced supply of amino acids from the digestive tract.

Although the effects of avoparcin on rumen fermentation, *in vitro*, are similar to those of monensin (*see Table 11.6*) it is becoming evident that there are differences in the mode of action of the two antibiotics. A fermentation product of a strain of the bacterium *Streptomyces candidus*, avoparcin is a water soluble glycopeptide antibiotic structurally related to the vancomycin group of antibiotics (McGahren *et al.*, 1980). Its primary action on the bacterial cell is to inhibit cell wall mucopeptide biosynthesis (Speth, Greenstein and Maiese, 1981), a mechanism of action consistent with other members of the vancomycin group of antibiotics (Perkins and Neito, 1974). Its antimicrobial spectrum is similar to that of monensin.

Characterization of the detailed ruminal effects of avoparcin is still in its infancy, but it is clear from studies undertaken at Newcastle that increasing the concentration of avoparcin in an *in vitro* fermentation system induces a significantly greater capture of energy (metabolic hydrogen) in useful products (*see Table 11.7*). The production of propionate was significantly

Table 11.7 THE EFFECT OF INCREASING CONCENTRATIONS OF AVOPARCIN IN THE MEDIUM ON THE RECOVERY OF METABOLIC HYDROGEN (2H) IN THE END PRODUCTS OF FERMENTATION IN AN *IN VITRO* SYSTEM IN WHICH RUMEN FLUID TAKEN FROM UNADAPTED SHEEP WAS INCUBATED FOR 22 h

	Avoparcin (ppm in incubation medium)			
	0	*2*	*8*	*20*
Proportion of 2H recovered in:				
(1) Useful end products				
$C_3+C_4+C_5$	0.340^{a}	0.344^{ab}	0.362^{ab}	0.367^{b}
microbial cells	0.086	0.086	0.087	0.087
(2) Waste products				
CH_4	0.549^{a}	0.509^{ab}	0.464^{bc}	0.429^{c}
H_2	—	—	—	—
2H balance	0.975	0.939	0.913	0.883

(Unpublished data of R.C. Macgregor).
[a,b,c]Values in the same row with different superscripts are significantly different ($P<0.05$)

Table 11.8 THE EFFECT OF INCREASING CONCENTRATIONS OF AVOPARCIN IN THE MEDIUM ON THE PRODUCTION (μmol/mmol HEXOSE (C_6) THEORETICALLY FERMENTED) OF VARIOUS END PRODUCTS OF FERMENTATION IN AN *IN VITRO* SYSTEM IN WHICH RUMEN FLUID TAKEN FROM UNADAPTED SHEEP WAS INCUBATED FOR 22 h

Production of:	*Avoparcin* (ppm in incubation medium)			
(μmol/mm C_6)	*0*	*2*	*8*	*20*
Methane	502^{a}	465^{ab}	420^{b}	388^{c}
Acetate	1125^{a}	1107^{a}	1086^{a}	1070^{b}
Propionate	312^{a}	328^{a}	361^{b}	365^{b}
n-Butyrate	253	264	259	266
n-Valerate	28^{a}	19^{b}	18^{b}	16^{b}
Total VFAs	1719	1717	1719	1718

(Unpublished data of R.C. Macgregor).
[a,b,c]Values in the same row with different superscripts are significantly different ($P<0.05$)

enhanced by 16% when the avoparcin concentration in the medium was 8 ppm, while the methane production was also reduced by 16% at that concentration and further reduced (23%) at 20 ppm (*Table 11.8*). When incorporated into the diet of sheep, avoparcin induced a reduction in the acetate:propionate molar ratio from approximately 3.5 to 2.5, an effect associated with a significant increase in the molar proportion of propionate (Macgregor and Armstrong, 1982). Furthermore, as has also been shown with monensin, avoparcin incorporation resulted in increased organic matter digestion in the rumen although there was no change in the total VFA concentration. However, reductions in the total VFA concentration have been observed (Froetschel *et al.*, 1981) when avoparcin was fed to sheep, and this resulted from significant reductions in the concentrations of acetate and butyrate in the rumen. The molar proportion of acetate was not affected, while that of propionate was significantly increased and that of butyrate significantly reduced. Unlike monensin, no changes in rumen fluid dilution rate were observed when avoparcin was fed, but there was a tendency for rumen volume to increase (Froetschel *et al.*, 1981; Macgregor and Armstrong, 1982), although in another experiment (Chalupa *et al.*, 1981) avoparcin increased rumen volume but decreased rumen dilution rate.

Table 11.9 THE EFFECT OF AVOPARCIN INCORPORATION IN THE DIET OF SHEEP ON PARAMETERS OF N DIGESTION

	Level of avoparcin in diet (ppm)	
	0	*45*
Rumen NH_3-N (mg/ℓ)	147	145
g microbial N/kg OM apparently digested in rumen	46.2	37.7
Feed AA-N degraded in rumen (g/day)	12.7	13.4
Total AA-N entering small intestine (g/day)	14.4	14.7
Net efficiency of AA-N uptake from small intestine	0.597[a]	0.687[b]

(From Macgregor and Armstrong, 1982).
[a,b]Values in the same row with different superscripts are significantly different ($P<0.05$)

In reference to the effect of avoparcin on the N transactions in the rumen, it can be seen in *Table 11.9* that rumen ammonia-N levels were not affected by avoparcin. The quantities of feed amino acid escaping degradation remained unchanged as did the total amino acid entry rate into the small intestine (Macgregor and Armstrong, 1982). When the amounts of amino acid apparently absorbed from the small intestine are expressed as a proportion of the total amino acid entry rate into that section of the tract, it becomes apparent that avoparcin has induced a significant enhancement in this parameter of absorptive efficiency. Microbiological assay for avoparcin in samples of digesta entering and leaving the small intestine of these sheep when fed avoparcin was carried out and microbiologically active avoparcin was detected in these samples. The implication inherent in these data is that avoparcin, in addition to inducing monensin-like responses in the fermentation of carbohydrate in the rumen, also acts in the small intestine resulting in an increased net uptake of amino acids therefrom.

The diet used in the previously mentioned experiment was high in forage (70% dried grass) and it would seem that the effect of avoparcin on the N

transactions in the rumen depend on the type of diet fed. When the effect of avoparcin on rumen fermentation was examined in sheep fed a high concentrate diet, decreases in ammonia-N and increases in alpha-amino-N levels were observed, but when fed a high fibre diet these parameters were not affected (Froeschel *et al.*, 1981). At present it would seem that as far as avoparcin is concerned, its site of action is not confined to the rumen, and indeed in view of its long history of successful use in non-ruminants this is not entirely surprising.

Conclusions

The future expansion of gastrointestinally active growth promoting feed additives depends primarily on further development of products that, in addition to being safe (a topic of some depth not dealt with here), must have adaptability such that they may be used in a wide variety of production situations. The best use of the newer products being considered is still not completely elucidated and greater knowledge of how they function will help resolve this problem. Because of their different modes of action, the possibility of synergistic effects of the feeding of two or more of these additives may exist, and indeed may play an important role in the further refinement of ruminant livestock production.

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12

SOME NUTRITIONAL ASPECTS OF HIGH YIELDING DAIRY HERDS

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Introduction

The high yielding dairy cow poses far more problems than scientists are currently capable of solving. One of the main factors limiting scientific advance is the paucity of high yielding dairy cows maintained under controlled conditions in which important variables, such as feed intake, milk output, liveweight (LW) change, etc. are accurately recorded. In the absence of such critical data, the scientist is obliged to extrapolate from cows of more moderate yield or rely on survey data. Such extrapolations can lead to potentially dangerous conclusions and may result in an artificial limitation being placed on such important factors as the maximum possible dry matter intake (DMI) and the potential of cows to catabolize depot lipids early in lactation and to replenish them during late lactation and the dry period. Such unwarranted constraints would affect the potential maximum milk yield.

DEFINITION OF HIGH MILK YIELD

Broster and Alderman (1977) suggested that a high milk yield could be defined as being of the order of 12000 kg/lactation but this would be exceptional and a high yield would normally be accepted as 7000 kg or more of milk. This yield level would be regarded in a European context as high but less so in certain states of the USA, particularly California and Arizona, or in Israel where such yields are commonplace (*see* Watkins, 1976; Wilson, 1978). For cows of smaller body size, a high yield situation will be at a considerably lower level. For Channel Island breeds a high milk yield is reached at about 4200 kg while for other dairy breeds, including the Ayrshire, a high yield is said to be attained at 5000 kg (Nix, 1982).

Tayler (1978) observed that only about 3% of British cows reach yields of 6000 kg per lactation and Wisselink (1979), reviewing western European

Table 12.1 ANALYSIS BY YIELD GROUPS (EXCLUDING CHANNEL ISLAND HERDS) (BOCM SILCOCK, 1982)

	Less than 4000	*4000–4500*	*4501–5000*	*5001–5500*	*5501–6000*	*6001–6500*	*6501–7000*	*More than 7000*	*Whole sample*
					(ℓ of milk/lactation)				
No. of herds	44	88	316	510	604	368	152	52	2134
Average no. of cows	74.80	83.11	92.99	98.07	102.73	104.54	104.91	108.00	99.37
Dry cow %	20.41	18.12	17.22	16.55	15.84	15.52	15.25	14.49	16.21
Winter milk %	44.87	46.99	48.61	49.39	50.33	50.88	51.16	51.70	50.00
Milk yield/cow (ℓ)	3738	4290	4780	5272	5751	6221	6727	7360	5621
Concentrates/cow (kg)	1270.43	1396.60	1544.47	1681.00	1889.25	2084.35	2280.52	2651.88	1850.05
Concentrates/ℓ (kg)	0.33	0.32	0.32	0.31	0.32	0.33	0.33	0.36	0.32
Margin over concs/cow (£)	332.29	382.70	432.70	474.72	507.68	547.49	583.27	614.33	498.06
Gross margin/cow (£)	260.42	311.91	354.49	389.23	420.02	445.56	467.93	410.90	407.17
Stocking rate (cows/ha)	1.81	1.87	2.04	2.05	2.12	2.14	2.22	2.26	2.10
Gross margin/forage ha (£)	471.36	583.27	723.15	797.92	890.44	953.49	1038.80	1154.63	855.05

countries, confirmed this view. These are likely to be pessimistic estimates as there are many practising dairy farmers whose cows are producing yields around 6500–7000 kg. A large amount of survey data confirms this fact (BOCM Silcock, 1982; Milk Marketing Board, 1982). *Table 12.1* highlights some pertinent information. It will be seen that for the 2134 non-Channel Island herds costed for the year ending December 1981 by the BOCM Silcock Dairy Enterprise Plan (DEP) costings service, 572 herds, involving some 60000 individual cows, were yielding in excess of 6000 ℓ while 52 herds had a mean milk yield of 7360 ℓ per lactation. Seventeen out of the 67 Channel Island herds also costed attained milk yields in excess of 4200 ℓ. There are, therefore, a large and increasing number of dairy farms in the UK which are in a high yield situation using the above definitions of a high yield.

Unfortunately, the data relating to commercial dairy farms are based on surveys and thus most of the evidence on the attributes of high yielding dairy cows remains subjective and descriptive rather than quantitative and critical. Nevertheless, a few experiments have furnished evidence on the performance of cows yielding 6000 kg plus per lactation (Jumah, Poulton and Apgar, 1965; Wagner and Loosli, 1967; Ekern and Vikmo, 1967; Tyrrell *et al.*, 1968; Wiktorsson, 1971; Kali and Amir, 1972; Ekern, 1972). However such studies remain the exception rather than the norm and almost all the work was conducted outside the UK.

There are, however, a growing number of farms where critical data are accurately recorded with herds managed under relatively normal commercial conditions. Three examples are the West of Scotland College Crighton Royal Farm at Dumfries, the East of Scotland College Langhill Herd near Edinburgh and the BOCM Silcock Dairy Demonstration Centre at Knaptoft in Leicestershire. At Knaptoft, 320 cows are maintained in three distinct separate herds with three different systems of feeding although the overall management and labour input are the same for all cows. When the present herd structure began in 1973/74, the mean milk yield stood at 5905 ℓ per cow for the total herd. By the year-end July 1982, this yield had risen to 6961 ℓ, an average increase of some 132 ℓ per cow per year.

Another aspect of high yield is whether this attitude refers to an individual animal or to a whole herd situation. Albright (1978) has illustrated the physical input:output relationships of the world's (then) highest yielding dairy cow, Beecher Arlinda Ellen. Earlier well-documented descriptions of outstanding cows also exist (*see* Odlum, 1945; Larsen and Eskedal, 1952; Boutflour, 1967). Furthermore, Broster and Alderman (1977) have presented data relating to two cows (Quantum and Heifer No. 55) at the National Institute for Research in Dairying managed by J.A. Bines and W.H. Broster respectively. Unfortunately, only a few such cows exist on a single research station. Indeed, the NIRD Annual Report for 1981 shows that with 452 cows and heifers an annual milk yield (National Milk Records (NMR)) of 4827 kg at 3.78% BF was recorded in 1979/80 which had risen marginally to 4919 kg at 3.87% BF in 1980/81 for some 461 cows and heifers combined. Thus even at the NIRD the herd as a whole is not within the definition of high yield used in this chapter.

Certainly to many farmers, and particularly pedigree breeders, the keeping of extremely high-yielding individual cows is a matter of pride and prizes, and may not always be based on sound commercial practice. This

Table 12.2 KNAPTOFT LACTATION PROFILE (NMR RESULTS, 1980/81)

	Herd 1			*Herd 2*			*Herd 3*		
Lact No.	*No. of animals*	*Milk yield (kg)*	*BF (%)*	*No. of animals*	*Milk yield (kg)*	*BF (%)*	*No. of animals*	*Milk yield (kg)*	*BF (%)*
1	58	5456	3.81	21	5558	3.42	15	5677	3.84
2	30	6995	3.83	10	6465	3.53	15	7219	3.63
3	27	7795	3.44	8	7253	3.71	12	7826	3.67
4	22	8451	3.79	6	8137	3.78	4	8197	3.52
5	15	8088	3.71	7	8556	3.69	5	8609	3.80
6	4	8441	3.67	1	10610	3.44	4	8640	3.48
7	6	7988	3.91	4	7981	3.46	3	9293	3.56
8	7	7795	3.64	—	—	—	2	7070	3.55
9	1	5687	3.30	1	8997	3.67	1	7914	3.52
10+	1	5894	3.79	1	8137	3.45	—	—	—
Total	171	6962	3.75	59	6907	3.56	61	7293	3.66

Herd 1: In 1980/81, 83 animals in this herd exceeded 7000 kg (48.5% of herd), 51 exceeded 8000 kg (29.8% of herd) and 20 exceeded 9000 kg (11.7% of total herd). Of these last 20 animals, one was in her second lactation, six third lactation, seven fourth, three fifth, two sixth and one seventh lactation.
Herd 2: In 1980/81 25 animals in this herd exceeded 7000 kg (42.4% of total herd), 13 exceeded 8000 kg (21.3% of total herd) and six animals exceeded 9000 kg (10.2% of herd). Of these last six, one was a fourth lactation cow, three were fifth and one sixth lactation.
Herd 3: In 1980/81, 33 animals exceeded 7000 kg (54.1% of herd), 21 exceeded 8000 kg (34.4% of herd) and nine exceeded 9000 kg (14.7% of herd). Of these nine cows exceeding 9000 kg, one was in her second lactation, two in their third, one fourth, two fifth, one sixth and two in their seventh lactation.

situation does not arise if there are sufficient numbers of such high-yielding animals in a particular herd so that individual attention is impractical. *Table 12.2* gives a detailed lactation profile for the three herds at Knaptoft taken from the NMR results for 1980/81 period. In this herd the yield profile is reasonably balanced. The high yield cows clearly form part of a normally distributed cow population and are not statistically exceptional.

3000 Gallon Club high yield survey (HY survey)

A recent survey carried out by the 3000 Gallon Club (Wood and Wilson, 1983) has specifically looked at high-yielding herds on the premise that a high-yielding cow is one which has given 750 kg of fat-plus-protein per lactation.

In 1980 the average 305-day yield of British Friesian cows in England and Wales was recorded at 5523 kg milk at 3.77% fat and 3.28% protein. The average yield of measured solids (fat + protein) was 390 kg in 305 days. During the same period, 394 cows in the national herd produced more than 750 kg of measured solids in a lactation of not more than 305 days. All but four of these animals were of a black and white breed which for convenience will be described as Friesian. These Friesians were distributed amongst 207 herds, and were the daughters of 177 sires. Their average lactation production to October 1981 is given in *Table 12.3*.

In an effort to gain more information about these very high yielding cows, a sub-sample of 67 animals was located in 24 herds which were

Table 12.3 MEAN LACTATION PERFORMANCE OF SOME HIGH-YIELDING FRIESIAN COWS

Lactation	*No.*	*Days in milk*	*Milk yield* (kg)	*Calving interval* (days)	*Dry period* (days)
1	375	298	6165	—	—
2	387	301	7815	387	63
3	364	301	8852	392	70
4	291	301	9386	395	66
5	205	298	9780	395	64
6	139	297	9888	401	76
7	83	295	9960	395	69
8	42	295	9960	398	80
9	11	254	9022	370	65
10+	10	300	9967	487	137

(After Wood and Wilson, 1983)

Table 12.4 AVERAGE HERD SUMMARY PERFORMANCE IN 1979/80 OF 24 HERDS COMPARED TO NMR OVERALL AVERAGE

Class	*No.*	*Milk yield* (kg)	*Fat* (kg)	*Protein* (kg)
		High yielding herds		
Cows	93.4	7748	300.6	253.3
Heifers	27.8	6444	252.6	210.7
		All NMR herds		
Cows	61	5762	229	197
Heifers	17	4763	189	163

(After Wood and Wilson, 1983)

visited by two club members working as a pair of observers during the winter of 1981/82. Details of the management were obtained from the owners, including any points on which the management of the individual animals differed from that of the total herd. *Table 12.4* presents the whole herd performance taken from the NMR records for these particular herds for that year. A number of the most salient points from this HY survey are highlighted below.

WINTER FORAGE

It is widely believed that most high yield herds are heavily biased towards silage as the most desirable form of winter forage and, out of the 24 herds visited, this was true of 22 farms. On one farm barn-dried hay was the usual winter forage and on the other it was normal sun-dried hay. It is therefore interesting to note that Seabrook (1981), in the sample used by the National Investigation into the Economics of Milk Production, showed that the ratio of hay and hay-based to silage and silage-based feed as the predominant winter forage was 47:53. However, in contrast, of the 1.7 million ha mown in 1980 in England and Wales, some 57% was cut for hay and only 42% for silage, the remaining 1% being used for artificially dried grass.

The quantity of hay made in the early 1970s remained fairly stable at 8.5 tonnes but this figure declined to an estimated 6.9 tonnes in 1980. Silage, on the other hand, has increased substantially. Nearly 8 tonnes of grass silage were harvested in 1969 but by 1980 this figure had more than trebled to an estimated 28 tonnes (Burns, Lewis and Randall, 1982). Correspondingly the quality of silage has also continued to improve slowly although less progress has been made in the upgrading of sun-dried hay. The improved quality of silage compared to hay (*Table 12.5*) means that it can contribute nutrients for both the maintenance and production for high-

Table 12.5 FORAGE EVALUATION (UKASTA/ADAS DATA COMBINED) BASED ON CHEMICAL ANALYSIS (MID OCT)

	1976	*1977*	*1978*	*1979*	*1980*	*1981*	*1982*
Hay							
No. of samples	2342	2710	1844	1584	1730	1922	1200
ME (MJ/kg DM)	9.0	8.7	8.7	8.8	8.6	8.6	8.8
CP (% DM)	10.1	9.5	9.4	10.1	9.4	9.5	10.3
Silage							
No. of samples	4806	7542	6188	6693	8619	10355	10823
DM (%)	27.6	27.8	27.4	26.0	26.2	25.0	27.4
ME (MJ/kg DM)	10.0	10.0	10.0	9.7	10.0	9.6	10.1
CP (% DM)	14.3	13.8	14.1	13.6	14.2	12.7	14.5

yielding dairy cows. The method of forage feeding was also examined in the HY survey and showed that silage was self-fed on 11 farms, otherwise it was cut and carried and fed in troughs under cover. Group feeding of the forage was practised on 15 farms. It seems clear that, provided forage quality is maintained, the method of feeding becomes increasingly irrelevant provided the grass is well conserved and the overall standard of feeding management is high.

It is also of interest to note that there appears to be some nutritional benefit where some hay is given at the same time as silage as this seems to enhance DMI and possibly aid digestion, and on nine of the 24 farms surveyed both hay and silage were fed. The other factor which was identified was that farmers were aiming for a 30:70 roughage:concentrate ratio on a DM basis in early lactation, a point recommended by most advisers (*see* Broster, Sutton and Bines, 1978).

CONCENTRATE FEEDING

The general principle with these HY survey herds was to have some feed on offer at all times whether it was forage, concentrates or a combination of the two. Concentrates were fed in the parlour twice daily on all farms and outside the parlour on 15 farms.

It is interesting to speculate the extent to which cows can be treated as individuals in a group situation, particularly as group feeding of concentrates was practised on 11 farms. Bryant (1980) has examined cow behaviour in group situations while Broster and Thomas (1981) have discussed individual versus group treatment. Most farmers with high-yielding herds tend to group their cows according to stage of lactation and

feed a common basal diet and then cater for each individual cow's requirement in the parlour by rationed feeding. To be more specific, at the BOCM Silcock Knaptoft Dairy Centre, the highest yielding herd (Herd 3), with a forecast milk yield for the year ending July 1983 of 8003 kg/cow at 39 g/kg BF and 88.5 g/kg SNF, and an average liveweight of 600 kg, is fed a basal diet of 2.0 kg of compound (Dairyfeed), 3.0 kg ensiled brewers grains and 2.0 kg sugar beet pulp plus 12.0 kg grass silage (DM 27%; Estimated ME 9.9 MJ/kg DM; Protein Degradability 88) and 4.0 kg purchased hay (DM 89%; Estimated ME 8.3 MJ/kg DM) to all 120 cows to provide maintenance + 9 kg of milk in early lactation. This is then 'topped up' with compound fed in the parlour twice a day and out of the parlour to cater for individual requirements.

Table 12.6 KNAPTOFT HERD 3—LITTLE-AND-OFTEN DAILY FEEDING ROUTINE

5 am	Compound in parlour
6 am	2 kg SBP + 1.5 kg hay in yokes
10 am	2 kg Dairyfeed
4.30 pm	Compound in parlour
5 pm	3 kg brewers' grains + 12 kg silage in yokes
9 pm	2.5 kg hay in yokes
3.6 kg Gold Label fed as part of basal diet out of parlour	

The other important practice at Knaptoft common to most high-yielding herds is little-and-often feeding and the feeding times for this herd are shown in *Table 12.6*. This concept would appear to be well accepted by commercial farmers. Of the 15 herds in the HY survey fed outside the parlour, two were fed three times, eight herds four times/day, three herds five times/day, one herd six and one herd seven times/day.

GRASSLAND MANAGEMENT

As far as grassland management was concerned, set stocking (full graze) was practised on 14 of the 24 HY survey farms. On three of the remainder, paddocks were strip-grazed. The case for supplementing grass with compound feeds during the grazing season has been debated at length and will not be reviewed here. Nevertheless in this survey compound was fed during the grazing season on all 24 farms, but on two it was withheld during peak periods of grass growth.

Table 12.7 SUMMER COMPOUND FEEDING RATES (YEAR ENDING SEPT 1982)

	Annual milk production (ℓ/cow)	*Stocking rate* (cows/ha)	*Apr.*	*May*	*Jun.*	*Jul.*	*Aug.*	*Sep.*	*Average for year*
			Concentrate feeding levels (kg/ℓ of milk)						
Costed herds	5616	2.20	0.32	0.17	0.18	0.20	0.25	0.31	0.33
Knaptoft	6859	2.50	0.40	0.14	0.16	0.20	0.39	0.46	0.39

Table 12.7 illustrates the summer compound feeding rate practised at Knaptoft in comparison with the average BOCM Silcock costed customer for the summer of 1982, while *Table 12.8* quantifies data related to supplementary feeding for summer milk production at Knaptoft over the past five years. It will be seen that around 40% of total milk production is achieved during the May to September period for this autumn-calving herd. It is likely that in most UK grazing conditions it is necessary to feed some concentrates throughout most of the summer period in order to achieve high yields, unless the rainfall distribution is exceptionally favourable to regular grass growth.

Table 12.8 KNAPTOFT SUMMER MILK PRODUCTION (SEPTEMBER YEAR END

	1977/78	*1978/79*	*1979/80*	*1980/81*	*1981/82*
Annual milk production (ℓ/cow)	6812	6758	7066	7110	6859
Summer milk production (May–Sept incl.)	2479	3033	2661	2747	2603
% summer milk	36.39	44.88	37.66	38.63	37.95
Total concs fed/cow (tonne)	2.63	2.63	2.54	2.71	2.70
Summer concs (May–Sept incl.) (kg)	606	783	559	748	703
Summer concs as % of total fed	23.04	29.77	22.00	27.60	23.00
Summer overall feeding rate (kg/ℓ milk)	0.24	0.26	0.21	0.27	0.27
Overall concs feeding rates (kg/ℓ milk)	0.39	0.39	0.36	0.38	0.39

The concept of Utilized ME (UME)/ha is providing a useful way of evaluating the grassland efficiency of farms. Leaver (1981) has indicated that the UME/ha has increased from 56.3 to 60.5 GJ between 1976 and 1980 based on MMB survey data. More recently Walsh (1982) has examined 34 herds in depth to consider the contribution made from efficient grassland production. This survey involved 4400 cows averaging in yield between 4200 and 7600 ℓ and indicated UME figures in the range 77–139 GJ/ha. In other words, a very high measure of grassland efficiency was achieved. *Table 12.9* shows clearly that the high-yielding herds had a much higher UME/ha figure than average-yielding herds. In addition they also used greater quantities of concentrates and had a higher financial return when expressed in terms of gross margin per forage hectare, indicating an overall greater degree of technical efficiency.

Table 12.9 CONTRIBUTION OF GRASS AND FORAGE TO ME REQUIREMENTS OF HIGH YIELDING HERDS

	Costed herds of average yield	*Costed herds of high yield*
Milk sales/cow (ℓ)	5621	7360
Concs fed/cow (tonne)	1.85	2.65
Stocking rate (cows/ha)	2.10	2.26
GM/ha (£)	855	1155
ME/cow obtained from concs (GJ)	21.3	30.5
UME/ha (GJ)	69.2	74.1

(After BOCMS, 1982)

BREEDING

Sixteen of the 24 herds in the HY survey used AI and that proportion (67%) is almost exactly the same as the percentage of herds in England and Wales which depend on AI. The mean calving index of the 24 herds in the survey was 384 days compared with 386 for all equivalent cows in the NMR population. This is an interesting finding as it counteracts the argument that high-yielding cows invariably exhibit fertility problems with extended calving intervals. Similar findings have been found at Knaptoft where the mean calving index for the three specific herds for a mean of eight years (1974–1982) stood at 384.2, 386.4 and 387.4 days respectively. A fertility analysis conducted on that farm by Traa and Esslemont (1977) indicated that there is no evidence that fertility is a problem with high-yielding cows provided that the standard of management is good.

The HY survey also revealed that 18 of the herds practised autumn calving. Three were based on a spring calving policy while the remainder showed no preference for a seasonal pattern.

The farmers were asked whether they used aids to control fertility and of the 24 farmers questioned, five used a computerized aid and, of these, four regarded the action list on NMR as such an aid. The fifth was developing his own system on a microcomputer. The most common form of aid to check fertility was the use of the breeding board in the parlour office and 14 farms used one. On 12 farms, a veterinarian made regular visits, usually fortnightly but occasionally less frequently.

HERD HEALTH

All herds in the HY survey practised teat hygiene and all except one practised dry cow therapy. The mean mastitis cell count for the group was 331000 cells/ml in a 12-month rolling mean compared with a 467000 cells/ml national average for the same period. As regards other metabolic disorders and production diseases the incidence of hypocalcaemia was high, although many farmers took precautions as a matter of routine. Lameness was the second most recurrent complaint. It seems that lameness, in all its various forms, is becoming an increasing problem with dairy cows spending more time on concrete. ADAS (1982) have estimated that lameness is costing the UK dairy industry some £16 m per year. However, it appears that the incidence of lameness is no more frequent in higher yielding animals than in others.

HIGH-YIELDING COWS

The cows which formed the basis of this HY survey were generally run with the herd, except in three herds where they were kept in a separate group. In four herds all cows were milked three times daily and in another four only the high yielders were milked in such a fashion. Brigstocke and Ford (1983) have reviewed the literature on the subject of milking frequency, particularly with regard to the increase in popularity in the UK of three

times a day milking. There is no doubt that, on available scientific evidence, it is most cost-effective to milk all cows in a herd throughout their lactations three times a day. If only cows in early lactation are milked three times a day and then changed to the normal two times milking, there is a significant and unavoidable drop in DMI and hence milk yield and this can be counterproductive. Despite this, the vast majority of farmers involved in this practice, for practical reasons, tend to only milk three times a day during the winter period. These authors also queried whether in the high-yielding situation three times a day milking will lead to the kind of increases in milk yield (10–20%) which have been found in lower-yielding herds, or whether the benefits found by increasing milking frequency in the USA and Israel are applicable under UK conditions given its extremely variable climate and winter forage quality.

LIVE WEIGHT (LW)

Some indication of the LW of the animal is crucial, as current estimates of the energy requirements and the DMI capacity of dairy cows are expressed as a rate per kg of LW (MAFF, DAFS, DANI, 1975). Thus if the figure taken for the average LW of the herd is too low or too high, it will result in either over- or under-feeding, leading to wasted feed or lost milk production. It is, therefore, surprising that weighing facilities were available on only one out of the 24 farms in the HY survey.

Work by Smith, Siviter and Whitby (1980), Broster (1980), Baber (1982) and Brigstocke *et al.* (1982) have all found independently that the LW of the average Jersey cow is not, as it is commonly assumed, 350 kg (*see* for example MAFF, DAFS, DANI, 1975) but is much nearer 420 kg for mature cows and 370 kg for heifers. It is also likely that similar under-estimates are made with large-framed black and white cows.

Estimates were available of LW immediately after calving for 44 cows in the HY survey where the average LW was 613 kg. It is likely that an assumed figure of 600 kg is adequate for this standard Friesian cow but for the more extreme dairy breed type (Jersey or Holstein) further data are needed.

Some farmers in this survey used a body condition score based on the NIRD technique (Mulvaney, 1977). Figures were available for 38 cows out of the 67 immediately before calving prior to the high yield lactation. These had an average body condition score of 3.12. The method of scoring has been described by Croxton (1976), who found that, in autumn calving cattle, the highest milk yields were associated with a score of 3.5 at calving. For further details on the whole aspect of fertility, body condition score and milk output an excellent summary paper has been provided by Haresign (1979).

Johnson (1982) has recently reviewed dairy cow nutrition and in particular has questioned whether liveweight change is either necessary or desirable. The pattern of liveweight loss is by no means constant in early lactation nor is its magnitude equal in all cows. Thus the daily rate of mobilization of body tissue varies most markedly between cows. Furthermore, little is known about the underlying physiological mechanisms

involved in the complex relationships between milk yield, dietary energy supply and body reserves. Johnson (1977) has shown that different patterns of feeding fixed amounts of concentrates in a restricted feeding regimen produce similar amounts of milk but different patterns and magnitudes of liveweight change.

Despite a number of questions about which further information is needed, most advisers believe that, in early lactation when feed intake is low, the intake of required nutrients cannot match the output in milk regardless of diet composition (e.g. Broster *et al.*, 1977). Withdrawal of body reserves is therefore inevitable and the cow is likely to be in a stressful condition (Broster, 1971; 1972). It is therefore sensible, as MAFF, DAFS, DANI (1975) have recommended, to allow for a maximum loss of 30 kg in total or some 0.5 kg/day in early lactation. However some debate concerns liveweight change in cows yielding in excess of 45 kg milk/day. This situation may also occur with high-yielding animals of smaller breed type yielding in excess of 25 kg milk/day (*see* for example Flatt and Moe, 1971).

PATTERN OF CONCENTRATE ALLOCATION

In this HY survey, steaming-up was defined as the feeding of 100 kg of compound in the period from 60 days before calving. However, as most farmers aimed to have their cows in condition before the end of the current lactation, only four herds adopted the practice. Overall during lactation about 18 kg of milk was generally expected from the basal diet, so that concentrates were fed at an average rate of 0.385 kg/kg of milk. This figure is similar to the herds yielding in excess of 7000 ℓ in *Table 12.1* (0.36 kg feed/kg of milk).

The subject of the level and pattern of concentrate input on subsequent milk yield has been extensively reviewed by Broster and Thomas (1981). They advocated a more flexible approach in order to 'develop' a lactation rather than a day-by-day approach to feeding. A number of experiments have suggested that an enhanced persistency of lactation can compensate for a reduction in peak yield (e.g. Johnson, 1977; 1979; Østergaard, 1979; Steen and Gordon, 1980). It now appears that any number of methods of concentrate allocation can work satisfactorily providing that the management on the farm is good (*see* Broster and Strickland, 1977; Rickaby, 1979; Strickland, 1979). This factor has certainly been borne out by the HY survey. Here it was found that lead feeding, defined as offering more than the current requirement before peak lactation yield, was practised for 27% of the cows. Feeding strictly according to yield was adopted for 47% and feeding according to stage of lactation regardless of yield was practised for 20% of the cows surveyed. One cow was fed concentrates *ad libitum*. The average milk yield at peak for the 67 surveyed cows was 47.6 kg/day and the yield averaged 16.7 kg/day when the cows were dried off.

It is also of interest to note that Broster (1979) has quoted a personal communication by P.D.P. Wood indicating that the shape of the lactation curve for an 8000 kg animal will be similar to the more average-yielding animal and that therefore the pattern of concentrate allocation may not be such a crucial factor.

GENERAL MANAGEMENT CONSIDERATIONS

In the HY survey the buildings, equipment and milking practice were much as to be expected from any well-run dairy enterprise. However, labour input was high; the most obvious characteristic of the management of these high-yielding herds visited was the close attention given to persuading animals to eat the large quantities of feed necessary to produce the high yields. On all farms the standard of stockmanship was very high and it was obvious to the investigators that the welfare of the herd was paramount.

Nutrient requirements

The HY survey has served to highlight many of the practices which farmers and advisers currently believe to be necessary for the attainment of very high milk yields. However, there remains a large amount of work to be done in terms of nutrient requirements expressed as feed inputs/day. Broster and Alderman (1977) have put forward some theoretical nutrient requirements for high-yielding cows. Jarrige (1978) has also suggested some estimates although both are based on theoretical rather than actual case studies. This unfortunately is still very much the case. The available evidence seems to indicate that high-yielding cows are not dependent on excessive inputs of concentrates when these are expressed as kg feed/kg milk. It seems that the efficiency of feed conversion to milk of such cows is high while their intake of DM is large. Broster and Alderman (1977), when discussing the 'response' to level of feeding, noted that more quantitative evidence is needed for cows yielding 40+ kg milk/day. Nevertheless there is no doubt that for most high-yielding herds (6500–7000 kg of milk/lactation) the available nutrient requirements are adequate within DMI constraints (MAFF, DAFS, DANI, 1975; ARC, 1980).

Broster (1979) noted that evidence on differences between breeds in the high-yielding situation is meagre. It is generally believed that the larger and the higher-yielding cow may be expected to eat more than the average (Monteiro, 1972; Broster, 1972). It is assumed that, in the absence of more critical data once allowance is made for milk quality, the Jersey has the same nutritional requirements as a Friesian but is merely two-thirds of its size. Initial work by Brigstocke *et al.* (1982) has indicated that the mature Jersey cow has a considerably higher DMI potential than available regression equations for appetite prediction would assume (*Table 12.10*). This work indicated that, in early lactation, animals peaking at 27.8 kg (sem ± 1.35) milk in week 7 of lactation were eating a total DMI of 19.17 kg (sem ± 0.77) for an animal of 420 kg LW, equivalent to 45.6 g/kg LW, which is much higher than the ARC (1980) estimate. It is also greater than observations by Khalifa, Prescott and Armstrong (1975) and Hutton (1963), where DMI equivalents of 36 to 40 g/kg LW, and 31.6 g/kg LW respectively, were found.

The use of fat-corrected milk (FCM) in the equation by Vadiveloo and Holmes (1979) greatly improved prediction. However the use of FCM had been found to be of little benefit over standard milk as an aid to effective prediction with Friesians or Ayrshires (Curran, Wimble and Holmes, 1970).

Table 12.10 PREDICTED AND OBSERVED DRY MATTER INTAKES OF JERSEY COWS (kg DM/DAY)

	Period of lactation	
	Early	*Late*
Predicted intakes from data of		
MAFF, DAFS, DANI (1975)	13.28	11.68
Vadiveloo and Holmes (1979)[a]	17.63	9.86
Vadiveloo and Holmes (1979) using fat-corrected milk[b]	18.46	10.25
Bines *et al.* (1977)	12.46	11.67
Observed intakes	19.17	12.76

Reference: Brigstocke *et al.* (1982)
[a]Source effect + 0.92 kg DM/day
[b]Fat-corrected milk calculated from ARC (1980)

A wider-ranging trial involving ten Jersey herds and 129 individually fed animals has indicated that, at peak milk yield (which occurred in week 6 of lactation), the mean DMI of these herds was 16.29 kg which was some 3.59 kg DM more than the Vadiveloo and Holmes (1979) equation which had proved the best predictor in the earlier trial (T.D.A. Brigstocke, unpublished data). It would therefore appear that many Jersey producers who use any of the current prediction equations to design their winter daily feeding programmes are in danger of under-estimating the DMI potential of their cows. Indeed, this general dissatisfaction with appetite predictions for Jersey cows may also apply to the other extreme dairy breed, the pure-bred Holstein.

However, in general, the available DMI predictions such as those given in ARC (1980) or from other sources are accurate for high, but not extremely high, yielding Friesians. For example the eight highest-yielding animals at the BOCM Silcock Development Unit, Barhill were consuming 21.8 kg DM/cow/day (sem ± 0.61) with an average liveweight of 606 kg and a milk yield between weeks 7 and 10 of lactation of 36.9 kg (sem ± 1.38) in December 1982. It seems that, with high-yielding animals, there is a remarkable similarity between the results with high-yielding Friesians and high-yielding Jerseys.

It could be argued that, as the national dairy herd now comprises 88.6% Friesians (MMB, 1982), the data relating to the Jersey is irrelevant. However, it is likely that with the increasing changes in the MMB Compositional Payment Scheme in favour of BF and Protein %, the future of the CI breeds is increasingly assured.

Brigstocke *et al.* (1982) noted that the energy content of the milk should be taken into account when planning suitable prediction equations with breeds of high BF potential. The calculation of energy-balance studies is therefore critical. In further unpublished data, mature Jersey cows were found to be consuming 21.97 kg DM/cow/day (sem ± 0.74) in week 7 of lactation when mean peak milk yield occurred at 23.91 kg/cow/day (sem ± 1.26). These seven freshly calved animals were weighed every ten days throughout the trial, which lasted the first ten weeks of lactation. On average they gained 6 kg/cow over this period. *Table 12.11* illustrates the theoretical situation, which would indicate surplus energy enough for 0.81 kg LWG/day instead of the observed 0.09 kg LWG/day.

Table 12.11 ENERGY BALANCE STUDIES WITH HIGH YIELDING JERSEY COWS

From *Bulletin 33* (MAFF, DAFS, DANI, 1975)
M_m = 8.3 + 0.091 LW. Assuming LW 429 kg, M_m = 47.34 MJ/day
Milk of 48 g/kg BF and 91 g/kg SNF requires 5.90 MJ/kg of milk.
Hence a milk yield of 23.91 kg requires 141.07 MJ ME
So Total ME allowances = 188.41 MJ/day
The ratio fed provided 224.03 MJ/day
Excess over that required for maintenance + milk production = 35.62 MJ/day
Taking the ARC (1980) figure of 26 MJ/kg LWG 1 kg LWG requires 44 MJ/day
Surplus energy = 0.81 kg LWG/day

(T.D.A. Brigstocke, unpublished data)

The reason for this discrepancy is not clear. MAFF, DAFS, DANI (1975) based its calculations on a requirement of 20 MJ/kg of LW gain. ARC (1980) have increased the energy value of empty bodyweight gain or loss to 26 MJ/kg. It may be that with Jersey cows even 26 MJ is on the low side. This assumes however that LW change in the early stages of lactation is representative of normal growth in respect of its proportion of protein and fat. Unpublished information has indicated that the slope of the relationship between LW change and energy balance is far steeper than has so far been accepted.

FARMING IMPLICATIONS

One of the most dramatic increases in dairy cow management over the past decade has been the growth in computerized management services designed to help the farmer not only from a financial viewpoint but also to enable him to provide suitable winter feeding regimens at least cost. Such a system is Dietplan which attempts to apply recent nutritional concepts on the farm.

The description of the system has been provided elsewhere (Lindeman *et al.*, 1980), while Wilson and Strachan (1981) and Filmer (1983) have quantified how the ARC (1980) protein system has been implemented into this computerized rationing system. The program optimizes for ME, based on MAFF, DAFS, DANI (1975) recommendations, and RDP and UDP (after ARC, 1980) on a dry matter basis within the DMI constraints at least cost. The DMI equation for early lactation used in the program is after Vadiveloo and Holmes (1979) and is as follows:

$$DMI = -0.64 + 0.43C + 0.015\,LW + 0.208\,MY + S$$

where C = concentrates fed (kg DM/day), LW = live weight, MY = milk yield and S = source effect (i.e. location and management of the herd).

A fully balanced diet is provided for five yield levels within each of the three stages of lactation (14–70 days, 71–200 days and 201 days +). Body weight losses in early lactation and gains in mid and late lactation are also taken into account. To show how the system operates, *Table 12.12* illustrates the nutrients required and supplied in the winter feeding regimen already referred to earlier for Herd 3 at Knaptoft, where the

principle of feeding is to provide a varied diet based on the little-and-often feeding concept. It should be noted that an attempt is made in Dietplan to ensure that some 15–20% of the total diet is being derived from such sources as sugar beet pulp, brewers' grains and the more digestible fibrous feeds. These feeds are becoming increasingly important in an effort to maintain the milk fat level and ensure optimum rumen fermentation patterns.

Table 12.12 EXAMPLE OF DIETPLAN PRINTOUT

Early lactation	*Target yield* (kg/day)									
	34 kg		*38 kg*		*42 kg*		*46 kg*		*50 kg*	
	Reqd	*Suppl*	*Reqd*	*Suppl*	*Reqd*	*Suppl*	*Reqd*	*Suppl*	*Reqd*	*Suppl*
DM (kg)	23.5	19.7	25.0	21.1	26.8	22.9	28.6	25.0	30.4	27.0
ME (MJ)	232	232	252	252	271	278	291	306	310	335
RDP (g)	1816	2266	1968	2462	2121	2727	2273	3012	2426	3296
UDP (g)	789	835	911	920	1034	1033	1156	1156	1278	1278
Ca (g)	116	166	127	180	139	200	150	221	161	242
P (g)	86	99	93	110	100	124	106	139	113	155
Mg (g)	32	39	35	42	37	46	40	51	42	56
Fibre/day (g/kg of LW)	206.1		197.1		186.8		177.4		169.4	
M/D of total ration	9.9	11.8	10.1	11.9	10.1	12.1	10.2	12.3	10.2	12.4

Knaptoft–Herd 3 (Breeders' Herd). Milk yield 8003 kg/cow at 39 g/kg BF and 88.5 g/kg SNF
Mean LW = 600 kg

A study of *Table 12.12* will reveal that, at the high milk yield levels in excess of 40 kg milk/day, there is an excess of ME but that the constraining factor on these rations is normally the UDP level. It would also appear that the nutrient requirements for the high-yielding animals in Knaptoft Herd 3 can be met within a lower DM intake than the prediction equation would suggest. However, what stands out in a comparison between this high-yielding herd and others with a low milk yield is that, apart from excess RDP which is inevitable if the winter forage regimen is based on silage, the lower-yielding herds have a much closer fit to nutrient requirements.

Dietplan is currently being utilized by some 4000 farmers each year and enables them to make sensible use of home grown feeds and purchased feed to allow the cow to express her full potential for performance. However, the inadequacies of the program for the high milk yield situation are only too clear. The computer is merely extrapolating from the more normal yield levels.

Conclusions

This chapter has indicated that, at high milk yield levels, there is a dearth of information upon which to base quantitative statements. It is an example of the commercial farmer being ahead of the research worker in the successful attainment of high yields both on an individual cow and on a herd basis.

The HY survey, upon which a large part of this chapter has been based, has given further information, albeit largely descriptive, on the role of the high-performing animals and on the importance of such cows within an

existing herd structure. It is clear that the attainment of high milk yields involves stimulating appetite to enable the cows to consume the very large quantities of nutrients needed. However, this can only be achieved by excellent management on the farm with close attention to every detail.

It has also illustrated that theoretical nutrient requirements are very satisfactory until milk yield exceeds about 7000 kg/lactation. Also, the requirements for different dairy breeds need further quantification and more work needs to be conducted on this topic.

It is likely that high milk yields will continue to be the best way for optimal economic performance. It is to be hoped that, within a few years, more critical nutritional data will be available to match more precisely these animals' potential. This chapter has only dealt briefly with DMI and ME requirements. The relevant needs for the major and minor elements, especially phosphorus, is much less well researched and unfortunately no data on this important aspect have emerged from the HY survey now reported.

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13

FEEDING FOR HIGH MARGINS IN DAIRY COWS

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Introduction

It might be assumed from the large amount of research and development work into dairy cow feeding, backed up by the government and commercial advisory agencies, that the answer to the question of how to feed dairy cows for high margins was straightforward! However, the answer partly depends on which 'margin' is used. An examination of any group of herds with high margins (per cow or per hectare) reveals a whole range of approaches to feeding being practised. As a result many different views prevail on the important priorities in feeding, but these often only reflect the narrow area of interest of the individual protagonists!

The very complexity of feeding management to some extent explains why simple answers cannot be given. Feeding is not only about nutrition, it also concerns the farmer in making the best use of the resources available to him. This includes grassland management, forage conservation, getting the right balance between purchased feed and milk output, the amount of investment in cows and cow places, and many other factors. Unfortunately, the management associated with the nutritional aspects of feeding is too often given prominence over the importance of the total feed inputs and milk output of the farm business as a whole. It is this latter relationship which explains much of the variation between farms in profitability.

Which margin is important?

There is much confusion over which measurement of profitability should be used when examining different systems of dairying. Ultimately the dairy farmer should be aiming to maximize profits relative to whatever is the most limiting resource available—land, labour or capital. On a small farm therefore, the profitability/ha is likely to be the most important measure, whereas on a large farm the profitability/£1000 capital invested may be more important.

Due to the difficulties of measuring and allocating costs (particularly overheads) and returns of the dairy enterprise, dairy costings schemes obtain an indication of profitability by measuring 'margins'. These represent the difference between the value of the outputs and some or all of the variable costs. The gross margin calculated on a per hectare basis is the most meaningful margin for most farms, but to simplify recording this is often reduced to a 'margin over feed and forage' (income from milk minus the costs of purchased feed and forage), or simply to the 'margin over purchased feed' (MOPF), which includes compounds, straights, forages and forage substitutes.

The most commonly used term is probably the 'margin over concentrates per cow' (MOC). This is a valuable indicator of the ongoing financial performance for the individual herd. In comparing the performance of different herds however, it has little meaning as illustrated in *Table 13.1.*

Table 13.1 COMPARISON OF TWO DAIRYING SYSTEMS WITH THE SAME MARGIN PER COW AND EFFICIENCY OF GRASSLAND UTILIZATION, BUT WITH A DIFFERENT MARGIN/ha

Annual milk sales/cow (ℓ)	5000	6000
Annual concentrates/cow (tonnes)	1.00	1.95
Annual stocking rate (cows/ha)	1.79[a]	2.05[a]
MOC (£/cow)	593[b]	593[b]
MOPF (£/ha)	1061	1216

[a]Based on a utilized ME (UME) of 70 GJ/ha
[b]Based on a milk price of 15 p/ℓ and a concentrate price of 15.75 p/kg

The two systems are equally efficient in grassland utilization, their MOCs are identical, but due to buying in more feed (some of which reduces the grass and forage requirement per cow) the second system has a higher stocking rate and a 15% greater margin/ha. The buying-in of other feeds such as hay, and brewers' grains which are not included in the MOC also add to the confusion when comparing the MOCs of different herds and systems. Therefore a more meaningful simple margin for comparing different herds where the grassland area represents a limiting resource is the MOPF/ha. This gives an indication not only of the economic efficiency of the use of purchased feeds, but also it indicates the efficiency of grassland use. For the purpose of this chapter this margin will be used for comparing different systems.

Use of feed resources

Reducing costs to increase profitability has a place on most farms, particularly where this involves a reduction in wastage. However, where a reduction in input costs results in a reduced output then it is unlikely to benefit profits. The method which is generally used by most dairy farmers to improve profitability is to increase the sales of milk, which means increasing feed inputs (*Figure 13.1*). Thus the size of business on a particular land area is increased; this is brought about by a larger herd size and higher milk yields per cow.

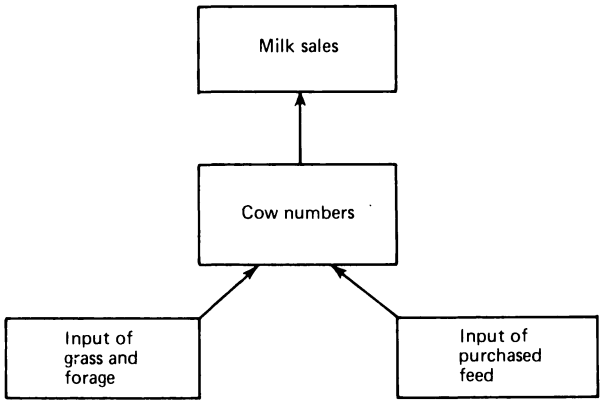

Figure 13.1 Diagram to illustrate how grass and forage utilized on the farm, and purchased feed determine the number of cows which can be carried, and the total farm milk sales

These effects can be illustrated from surveys of dairy herd performance. In *Table 13.2* a comparison of herds is made on a gross margin/ha basis (total output minus total variable costs). This clearly shows how the top 25% of producers developed a much larger business on a given land area than the bottom 25%. Not only did they utilize 62% more dry matter from each hectare of land, they also purchased 50% more concentrates giving a 58% increase in total feed input. This allowed 45% more cows to be carried producing in total 72% more milk. The net effect of this approach was an MOPF/ha of £1134 for the top 25% compared with £591 for the bottom 25% (gross margins/ha £970 and £444 respectively).

Table 13.2 A COMPARISON OF TOP AND BOTTOM 25% OF HERDS SELECTED ON A GROSS MARGIN/ha BASIS

	Top 25%	*Bottom 25%*
Yield per cow (ℓ)	5765	4863
Concentrates per cow (tonnes)	1.83	1.77
Stocking rate (cows/ha)	2.31	1.59
Concentrate input/ha (tonnes DM)	3.6	2.4
Grass and forage utilized/ha (tonnes DM)[a]	7.3	4.5
Total feed input/ha (tonnes DM)	10.9	6.9
Milk sales/ha (ℓ)	13317	7732
Milk sales (£/ha)	1682	965
Purchased feed costs (£/ha)	548	374
MOPF (£/ha)	1134	591

(Data calculated from MMB, 1982)
[a]Based on the estimated UMEs of 79 and 48 GJ/ha

The costs of the different feed resources vary considerably. On a cost per unit of metabolizable energy (ME) basis, the relative costs of grazed grass, conserved forage and compound concentrates on farms with high levels of grass utilization are approximately in the ratio 1:2:4½ (where poor standards of grassland management are achieved the ratio is much closer).

Increasing the level of grass utilization on the farm as grazed grass or forage will consequently have a much greater impact on profitability than by purchasing the same amount of ME in the form of compound concentrates.

Grass and forage

It is unfortunate that many farmers do not make a good job of producing and utilizing grass and forage. Inadequate fertilizer levels, a failure to match cow numbers to grass growth during the grazing season, and excessive losses during the ensiling process and silo emptying all contribute to the poor average level of utilization on farms. This amounts to only 50–60% of what is possible with good management.

The utilization of grass on individual farms can be calculated from the following information given in farm costings—the annual milk sales per

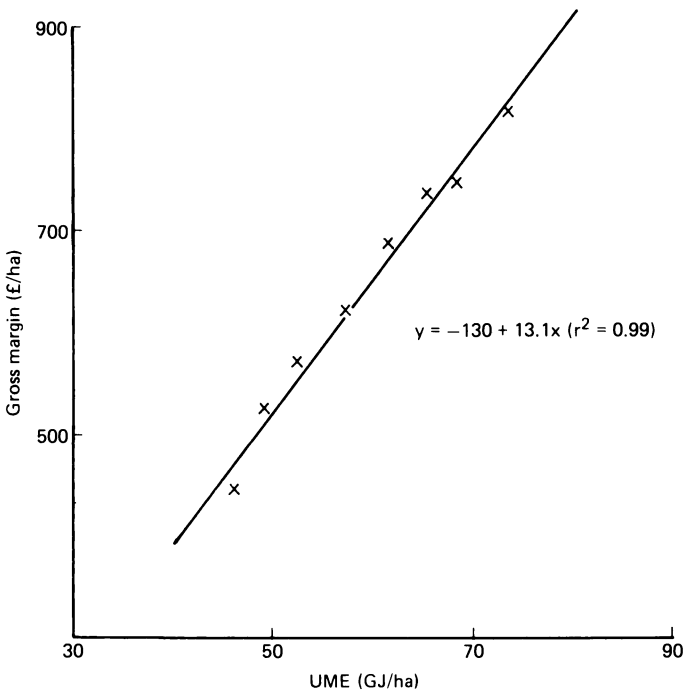

Figure 13.2 The relationship between UME and gross margin/ha. The gross margin/ha increases by £13.1/GJ increase in UME. Original data taken from nitrogen fertilizer/gross margin data of MMB (1982)

cow, the annual purchased feed input per cow, and the annual stocking rate. This is expressed as the utilized ME (UME in GJ/ha), and can be converted to the tonnes of grass dry matter utilized/ha. The average level of UME on costed farms is about 60 GJ/ha (equivalent to 5.6 tonnes DM/ha), with a range from 40–90 GJ/ha (3.7–8.4 tonnes DM/ha).

In farm costings there is a close relationship between the UME and the gross margin/ha (*Figure 13.2*), which increases by about £13/GJ increase in UME (about £140/tonne DM). The incentive to increase output from the dairy herd by increasing the UME is therefore substantial.

Purchased feeds

The polarization of views on the optimum level of purchased feed (in particular compound concentrates) for dairy cows generally results from a failure or refusal to understand their function in the farm business as a whole.

In experiments where high quality silage is offered *ad libitum* the response in milk yield to increased concentrates is often less than 1 kg milk/kg additional concentrates (Gordon, 1981). As the milk price/concentrate price ratio is close to 1:1, this response is often cited as an argument for not feeding concentrates at more than low to moderate levels (e.g. 6–9 kg/day).

However, concentrates not only lead to increased milk yields; some of this energy is partitioned into live weight, and the concentrates also reduce silage requirements (*Table 13.3*). The live weight has a value in producing

Table 13.3 THE EFFECT OF CONCENTRATE LEVEL ON DAIRY COW PERFORMANCE AND SILAGE INTAKE OVER 20 WEEKS

	Concentrate level (kg/day)	
	6	*12*
Milk yield (kg/day)	25.6	29.5
fat content (g/kg)	39.4	38.1
protein content (g/kg)	32.4	33.7
Liveweight change (kg/day)	0.13	0.19
Silage DM intake (kg/day)	11.1	8.1

(From Moisey and Leaver, 1982)

milk in the next lactation through the mobilization of body tissue (Land and Leaver, 1981), and also when the cow is sold for meat. More importantly, the substitution of concentrates for forage intake reduce the requirement for forage. The net effect is that a higher purchased feed input can also lead to an increase in both the stocking rate and the MOPF/ha.

Relationship between MOPF/ha and feed inputs

The ME system allows a theoretical model to be constructed to interrelate the annual milk sales per cow, the purchased feed per cow and the stocking rate to test the sensitivity of milk outputs and margins to changes in feed inputs. This is useful in examining different strategies for milk production. The simple model is as follows:

$$\text{Annual milk sales/ha} = \frac{U + CS - MS}{L}$$

where U = annual UME (GJ/ha) from grassland
C = annual ME from purchased feed (GJ/cow)
S = annual stocking rate (cows/ha)
M = annual ME for maintenance, pregnancy and growth (GJ/cow)
L = ME content of milk (GJ/ℓ).

Table 13.4 THE INTERRELATIONSHIP OF CONCENTRATE INPUT, MILK SALES, AND UME WITH STOCKING RATE AND RELATIVE MARGIN OVER PURCHASED FEED/ha (MOPF)

Concentrate input (tonnes/cow)	1.00	1.75	2.50
Milk sales (ℓ/cow)	5000	6000	7000
UME (GJ/ha)		*Stocking rate* (cows/ha)	
60	1.54	1.65	1.78
80	2.05	2.20	2.37
100	2.56	2.75	2.97
		Relative MOPF/ha[a]	
60	100	114	130
80	133	152	173
100	166	190	217

[a]Based on a milk price/concentrate price ratio of 1:1

From the annual milk sales and the annual purchased feed/ha, the MOPF/ha can be calculated as in *Table 13.4*. The milk sales/concentrate inputs which have been assumed, approximate to the averages seen in farm costings. They represent a response of 1.33 kg milk per additional 1 kg of concentrates which is greater than that reported in many experiments. The probable explanation for this is firstly because the average quality of forages on farms is poorer than those fed in experiments, and secondly the forages are often offered in restricted amounts.

The results show that:

(1) at any concentrate input/milk yield level, an increasing UME substantially increases stocking rates and MOPF/ha;
(2) at any level of UME, increasing concentrate input partly leads to increased milk yields and partly to increased stocking rates which together increase MOPF/ha.

Inevitably the model only indicates the relative effects of grassland utilization, purchased feeds and cow numbers on MOPF/ha, and not necessarily on the measure of profits that the farmer is ultimately interested in. In practice the limiting resources on the farm will to some extent also dictate the system of management as discussed earlier.

If the total contribution of grassland is a limiting factor, as on small farms or farms with poor grassland production potential, then buying purchased feed is an obvious method of increasing the size of the business, allowing more cows to be kept at higher milk yields per cow. On larger farms where the amount of capital or the availability of skilled labour represent the major limiting resources, then there will be a tendency to operate on simplified management systems with lower purchased feed inputs and lower milk yields per cow, and a much greater reliance on grass and forage in the annual feed input per cow.

The same model can also be used to study the effect of a change in the milk price/concentrate price ratio on the MOPF/ha (*Table 13.5*). This shows that the additional margins/ha from buying in more purchased feed cease at a ratio below 0.7. However a variety of factors are likely to deter dairy farmers from progressing along the high food input/high milk output road at ratios considerably above 0.7. The increased fixed costs associated with carrying more cows on the same land area in the form of extra

Table 13.5 EFFECT OF CHANGES IN THE MILK PRICE/CONCENTRATE PRICE RATIO ON THE RELATIVE MARGIN OVER PURCHASED FEED/ha (MOPF) AT A UME OF 80 GJ/ha

Concentrate input (tonnes/cow)	1.00	1.75	2.50
Milk sales (ℓ/cow)	5000	6000	7000
Milk price/concentrate price ratio		*Relative MOPF/ha*	
1.0	100	114	130
0.9	88	98	110
0.8	75	82	90
0.7	63	66	69
0.6	50	50	49

housing, labour, machinery and equipment, and the financing of the extra cows are strong deterrents. Also on predominantly grass farms there is a limit to the number of cows which can be maintained due to the amount of slurry produced and to the amount of treading and poaching of land. The critical ratio will differ for different farmers and will depend on the resources and business structure of the farm.

Thus, the general trend in dairying in the near future is likely to continue in the same direction with fewer dairy farmers each carrying more cows at high milk yield levels. This will partly be brought about through these farmers acquiring more land, and partly as outlined above, by each farmer increasing grassland utilization and purchasing more feed. This trend inevitably leads to increasing levels of milk output nationally, and increased surpluses of milk and dairy products within the EEC. In this case therefore the trends in milk production systems which are beneficial to the individual farmer, do not appear to be beneficial nationally or for the EEC. To curtail this trend would need a substantial reduction in the milk price/concentrate price ratio through manipulation of the milk pricing mechanism, otherwise some form of quota system would have to be introduced.

The management necessary to produce high margins

The preceding outline of strategies for producing high margins/ha has highlighted the importance of obtaining high levels of UME/ha, and of having the annual milk sales per cow, the stocking rate and the purchased feed input in balance. The theoretical model described can be used to set targets for individual herds, the choice depending on the resources available and on the ability and interests of the farmer. The achievement of the targets will then depend very much on the standard of day to day management of the herd.

The following is a summary of some of the important management factors seen in herds with high margins.

ACHIEVEMENT OF HIGH UME LEVELS/ha

The management necessary to produce and utilize high levels of herbage are well documented. The low levels of utilization seen on many farms are

generally due to inadequate fertilizer nitrogen levels (should be over 2 kg/ha/day); to understocking in early season combined with overstocking thereafter (should be over six cows/ha in early season and under four cows/ha thereafter); and to large losses during the ensiling and silo emptying process (these are often over 20% of the DM ensiled).

GRASS AND FORAGE AVAILABILITY

The achievement of high dry matter intakes of grass and forage is essential. Cows should not be restricted in the amount of grass or forage available to them, and this should be of high quality (over 10 MJ ME/kg DM). The failure to achieve these two objectives contributes largely to the poor milk yields per cow seen in many herds.

CONCENTRATES AND MILK YIELD

The initial targets of concentrate input and milk yield may not be achieved unless they are carefully monitored and appropriate action taken. The milk sales of the herd should be checked weekly against concentrate usage to see whether they are according to target and if not then remedial action should be taken.

HIGH CONCENTRATE SYSTEMS

Where a high input/high output system is practised, attention must be given to the system of concentrate feeding. At levels over 9 kg/day of concentrates, consideration should be given to systems of out of parlour feeding (in troughs, feeding passages, out of parlour dispensers or in complete diets). More frequent feeding will prevent reductions in forage intake and possible depressions in milk fat content.

FERTILITY AND HEALTH MANAGEMENT

High margins cannot be achieved unless the cows have a satisfactory calving index of under 380 days (for example a lactation average of 7000 kg at 400 days represents an annual milk sales level of only 6387 kg!). The incidence of health problems must also be kept to a minimum for high levels of performance.

Conclusions

The farmers who at present are producing the highest margins/ha, are running a large business/ha of land through utilizing large amounts of grass/ha and purchasing substantial amounts of other feeds—particularly concentrates. This enables them to have high stocking rates and high levels of milk sales per cow. Inevitably this approach leads to large outputs of

milk/ha. Whether this strategy continues to be the most profitable will depend on the future milk price/concentrate price ratio, and whether any restrictions (quotas) are introduced to control the national levels of milk production. Having the correct strategy for the particular farm business is only the first step towards high margins. The standard of day to day management of the herd ultimately determines whether the targets are achieved.

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14

COPPER IN ANIMAL FEEDS

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Introduction

The use of copper in animal feeds has become quite controversial over recent years due to the conflict of interest between its value as an essential nutrient and its potential adverse effect on the environment. In order to clarify the issues involved, a workshop was organized by the EEC with specialists from the various countries of the community. This workshop, held in Bordeaux in October 1980, examined the use of copper as a growth promoter for pigs and the consequences to the environment of the resulting slurry with enhanced contents of copper. Simultaneously consideration was given to the effects of copper-containing sewage sludge on the soil, the plant and the animal.

The stated objectives of the workshop were the following (EEC, 1981):

(1) animal nutrition: to consider how much copper is needed in pig feeding;
(2) animal physiology: to consider the influence of copper on pig growth and where in the animal it is stored;
(3) agronomy: to evaluate the risks to the soil–plant–animal system in introducing copper in animal feed rations;
(4) effects on consumers: to assemble information on the possible effect on consumers of eating meat from pigs receiving extra dietary copper.

From the papers presented and the discussion that followed, the workshop reached the following conclusions.

(1) The weight of evidence favours the continued use of copper as a feed additive in order to improve the efficiency of pig production. The information on the amounts needed and the ages of the pigs at which it should be administered is less clear cut, especially with regard to whether the maximum level required is 125 mg/kg or 200 mg/kg. Therefore there is insufficient evidence to justify altering the present position on scientific grounds.
(2) The problems of the use of copper as a growth promoter in pig feeds

are long term in nature and will require considerable further investigation to solve them.

(3) Copper is required for the development of all animals but the mechanisms by which added copper promotes growth in pigs are not fully understood.

(4) Copper is known to interact strongly with other elements in animal nutrition; for example the administration of higher levels of zinc and iron decreases the toxic effects of copper and its level in the liver. With ruminants there are very marked interactions between copper, molybdenum and sulphur. Such interactions can influence the effects of copper applied to pasture in slurry or sludge on the health and performance of grazing animals.

(5) The forms of copper in animal faeces, slurry and sludge are not completely known, nor their availability to plants or to animals when grazing contaminated swards.

(6) All the copper applied to land may not always be accounted for by analysis of the soils. The error in assessing the amounts applied and in sampling and analysing the soil should be assessed. Any pathways of loss should be identified, including the forms of copper that may be lost by various mechanisms.

(7) The effects of two or more heavy metals may be additive, independent or interactive. In the absence of detailed information on multi-element systems the use of the additive concept for applying copper and other heavy metals to soils tends to lead to more conservative applications.

(8) For the consumer, the enhanced levels of copper in the livers of pigs receiving supplementary copper are no greater than in some other animal livers, and do not adversely affect the health of consumers.

(9) If the present policy of disposing of animal wastes on limited areas is continued, the application of slurry from pigs receiving supplementary copper could increase the concentrations in the soil to unacceptably high levels within a finite time. The use of lower levels of supplementation will increase the time before toxic amounts are present but the major factor in determining the amount of copper applied to the land is the intensity of pig production in the area.

(10) The most desirable solution to this problem is to remove the copper from the slurry before disposal to land if this becomes feasible and economic. No current work is known which would allow this, but a close watch should be kept on appropriate technology.

(11) Although some experimental work has demonstrated that the ingestion by sheep of herbage heavily contaminated with slurry from pigs receiving added dietary copper can cause toxicity, these problems can be overcome by proper slurry management and animal husbandry. Breeds of sheep vary much in their susceptibility to deficiency and excess of copper in the diet, and lambs more so than adult sheep.

(12) A uniform solution for all countries is difficult to foresee because of variations in conditions. For example, the large areas of copper deficient soils would be expected to benefit from additions of copper as salts, in slurry or in sewage sludge, whereas no further copper should be added in other areas.

From these conclusions, the workshop made the following recommendations.

(1) There is no scientific basis to recommend changing the existing directives on the use of copper as a feed additive for pigs; Annex II of Directive 70/524 permits up to 200 mg/kg feed.
(2) Until further information is available on the behaviour of copper and other heavy metals in soils and plants and on animals, the framing of uniform conditions for land disposal cannot be done.
(3) Further investigations are urgently required into the mode of action of copper as a growth promoter and the behaviour of copper in slurry and sewage when applied to land.
(4) Investigations are needed on the forms of copper in pig slurry and sewage sludge with a view to devising methods for their removal.
(5) The technological problems of removing copper from pig slurry should be put to those concerned with these areas of work.
(6) There is a need to continue looking for alternative growth promoters, which will substitute directly for copper and have no environmental impact.

Despite the clear conclusion that there was no scientific evidence to change the existing directives on the use of copper for pigs, in June 1982 the Annex II entry was modified, as was the Annex I entry of EEC directive 70/524 for the maximum level of copper in sheep feeds. Details of the relative part of the directive are shown in *Table 14.1*.

Table 14.1 ADDITIVES DIRECTIVE EEC 70/524

	Maximum level of copper allowed in complete feedstuffs	
	Up to June 1982	*Post 40th amendment June 1982*
Annex I Pigs	125 mg/kg	125 mg/kg
Sheep	50 mg/kg	20 mg/kg
Other species	50 mg/kg	50 mg/kg
Annex II Pigs	200 mg/kg	200 mg/kg up to 4 months of age

The reason given for this change in the directive was concern about the environment and the danger of copper toxicity in sheep. This reason must be greeted with a great deal of surprise considering the information which emerged from the Bordeaux conference and published elsewhere. This chapter will therefore review some of this work particularly in relation to the effect of copper in sewage sludge and pig manure on plant copper content, copper deficiency in sheep and cattle, factors affecting copper absorption by plants and animals and finally the economic effect of the use of copper in pig feeds.

The effect of copper in sewage sludge and pig manure on plant copper content

In his Bordeaux paper entitled 'The application of copper in sewage sludge and pig manure to agricultural land in England and Wales' Unwin (1981) stated that the natural level of copper as measured by extractable EDTA in

the soils of England and Wales was usually less than 5 mg/ℓ, and thus most soils could tolerate the addition of up to 280 kg of copper/ha without any significant reduction of the cropping potential of the land. In the UK, only about 35% of pigs are stocked at rates which would result in an average copper addition in the soil of over 2 kg/ha/year, when the pigs were fed a diet containing 200 mg/kg of copper. The area of land which currently receives more than 5 kg of copper/ha/year is extremely small and thus at this rate, this copper addition could continue for 56 years before the 280 kg of copper level was reached. While most soils are adequately supplied with copper for crop growth, these soil levels are often not high enough to meet the copper requirements of grazing livestock. It thus appears that, certainly within the UK, there is much more danger of copper deficiency than copper toxicity. Potentially, there seems to be more danger from sewage sludge with a copper content of 36–2889 mg/kg DM than from slurry from pigs receiving 200 mg/kg copper, where the copper content of the slurry would be between 600–900 mg/kg DM. *Table 14.2* indicates that even after

Table 14.2 COPPER CONTENT OF GRASS (mg/kg IN DRY MATTER) GROWN ON SOIL PREVIOUSLY SUBJECTED TO HEAVY DRESSINGS OF PIG SLURRY

	Soil copper (mg/ℓ EDTA Cu)	*Grass content* (mg/kg DM)					
		1977		*1978*		*1979*	
		Mean	*Max.*	*Mean*	*Max.*	*Mean*	*Max.*
Control	2	9.7	13.9	10.6	16.9	11.4	14.3
High slurry	42	18.2	40.2	15.6	31.1	12.7	13.9

(From Unwin, 1981)

a high dressing of pig slurry, the copper content of forage crops grown on that land falls back to normal within three years.

Webber *et al.* (1981) indicated that when sewage sludge containing 1048 mg copper/ℓ was applied to plants at a rate equivalent to either 298 kg copper/ha or 596 kg copper/ha or 895 kg copper/ha, it had a depressing effect on plant yield and that copper levels within the plant built up to a level in excess of 18.2 mg/kg DM. However, Delas and Dartigues (1970) showed that this marked depression in growth only occurred in acidic soils. When the soil was limed the addition of 240 mg copper/kg soil had no marked depressing effect on plant growth (*Table 14.3*).

If one assumes that plant copper level needs to rise to the region of 15–20 mg/kg DM before any depressing effect will be seen on crop growth, then data presented by Dam Kofoed (1981) and shown in *Table 14.4*

Table 14.3 EFFECT OF COPPER APPLICATIONS AND LIME ON THE WEIGHT INCREASE OF VINE CUTTINGS GROWN IN POTS (g/POT)

	Non-limed soil (water pH 4.8)			*Limed soil* (water pH 6.1)		
	Initial weight	*Final weight*	*Increase (%)*	*Initial weight*	*Final weight*	*Increase (%)*
Control without copper	4.31	8.12	88.3	4.64	9.01	94.1
Application of 240 mg of copper/kg of earth	4.57	5.31	16.1	5.13	9.40	83.2

(From Delas and Dartigues, 1970)

Table 14.4 CONTENTS OF COPPER (mg/kg DM) IN DIFFERENT CROPS WITH AND WITHOUT APPLICATION OF SLUDGE TO THE SOIL

Crop	*Control without Cu*	*Household sludge* (21 kg/Cu/ha)	*Industrial sludge* (134 kg/Cu/ha)	*Fertilizer without Cu*
		Copper content (mg/kg DM)		
Barley, grain	4.0	4.8	4.9	3.6
Barley, straw	4.1	4.4	3.9	4.1
Oats, grain	3.6	4.3	3.9	3.1
Oats, straw	3.1	4.6	4.2	4.5
Grass	6.4	9.3	8.6	8.1
Beet, root	7.2	7.0	7.4	8.2
Beet, top	9.2	11.8	12.0	10.8
Potato	7.4	8.8	8.8	6.9
Kale, leaves	8.8	9.7	8.8	10.1
Kale, stalk	6.6	6.9	7.4	5.8
Carrot, root	9.3	10.1	9.4	11.0
Carrot, top	12.7	13.0	14.2	12.2
Cabbage	5.6	7.8	5.5	4.9

(From Dam Kofoed, 1981)

indicate that up to at least 134 kg of copper can be added/ha without the crop level exceeding 15 mg/kg.

Davies (1981) reported that in field trials, less than 0.1% of copper added to the soil in sludge could be recovered and the addition of 443 kg of copper/ha only increased the copper content of the herbage from 4.6 mg/kg DM to 6.8 mg/kg DM.

Thus, it would appear that whilst a potential problem of copper build up in the soil must be recognized, the likelihood of this reaching critical proportions from the use of pig slurry is extremely remote, particularly under UK conditions. It is surely preferable to approach this problem by controlling the use of slurry and sludge than by penalizing the profitability of the pig farmer.

Copper deficiency in sheep and cattle

While the problem of toxicity in sheep grazing land that has recently been treated with slurry or sludge should not be ignored, Bremner (1981) indicated that, providing care is taken to minimize surface contamination of the plant with the slurry by applying the slurry only when the grass is short and at a reasonable length of time before sheep are allowed to graze, the pasture copper levels should remain within a reasonable and acceptable range. It would appear that throughout many parts of Europe, there is a much greater danger of sheep suffering from copper deficiency than copper toxicity, which is hardly surprising when one considers the distribution of copper in the soil. It is, therefore, most surprising that the EEC have seen fit to impose a maximum of 20 mg/kg of copper in sheep feeds. In order to comply with a maximum of 20 mg/kg no copper can be added to the compound feed and ingredients which may on occasions contain high levels of copper must be excluded. This means that on average sheep feeds would only contain some 10–12 mg/kg with many samples falling as low as 5 mg/kg if one is to ensure that no samples exceed 20 mg/kg.

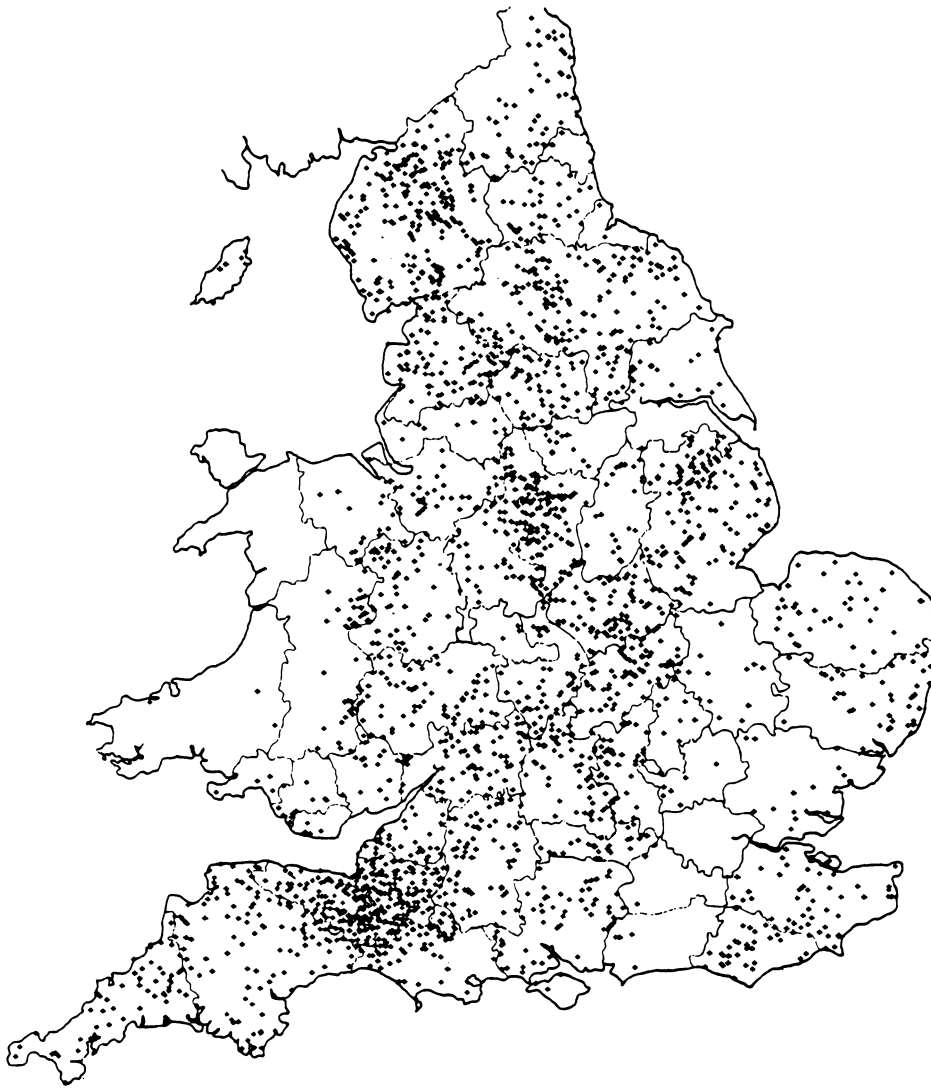

Figure 14.1 The distribution of bovine hypocuprosis/hypocupraemia over the period 1977–1980 (MAFF, 1982). No. of herds = 4088. (Blood copper ≤ 0.08 mg/100 ml whole blood)

Figures 14.1 and *14.2* show the distribution of bovine hypocuprosis/ hypocupraemia in England and Wales in the period 1977–80. *Figure 14.3* illustrates the monthly incidence of copper deficiency in the Scottish sheep flock and Suttle (1982) reported a similar picture in bovine species in Scotland, with up to 40% of animals showing lower than normal blood plasma copper levels at certain times of the year.

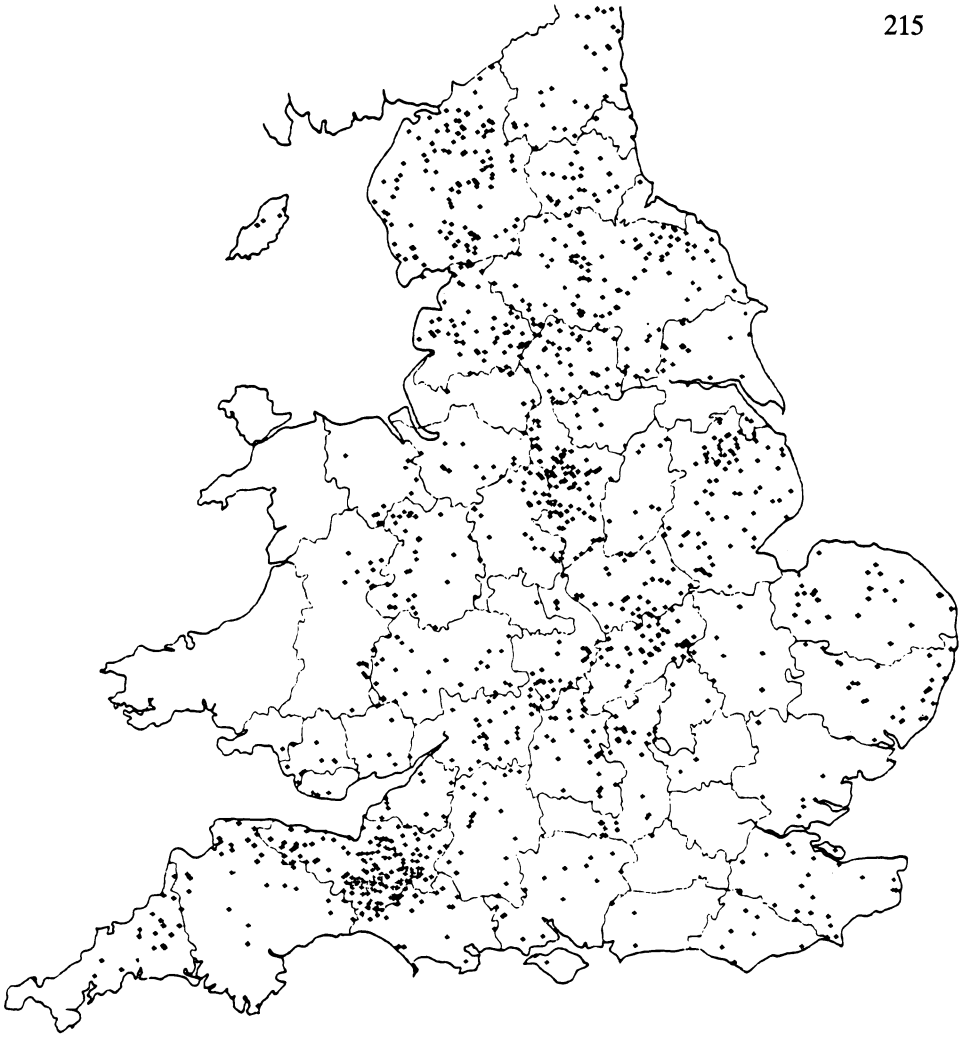

Figure 14.2 The distribution of bovine hypocuprosis/hypocupraemia over the period 1977–1980 (MAFF, 1982). No. of herds = 1748. (Blood copper $\leqslant$ 0.06 mg/100 ml whole blood)

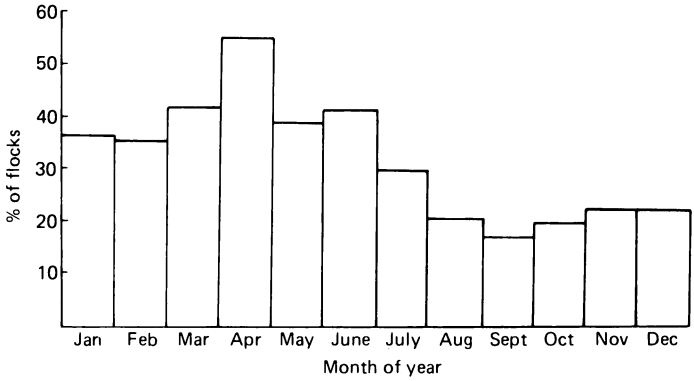

Figure 14.3 The proportion of the Scottish sheep flock which showed subnormal (i.e. less than 0.6 mg/ℓ) plasma copper concentration during 1981 (From Suttle, 1982)

THE EFFECT OF COPPER ANTAGONISTS

This widespread picture of copper deficiency in cattle and sheep is clearly not due solely to low soil copper levels but is complicated by the presence of antagonists to copper within the soil, which are then absorbed into the forage crop and subsequently consumed by the animal. These antagonists have been listed by Bremner and Mills (1981) as being molybdenum, sulphur, zinc, iron and cadmium. Maps published in the *Wolfsen Geochemical Atlas of England and Wales* (1978) show the distribution of molybdenum and copper and from a study of these maps it can be seen that there is an area of land spreading up from Somerset into the Midlands and the South Pennines where molybdenum is likely to interfere seriously with copper availability. This picture relates very well to the distribution of bovine copper deficiency, shown in *Figures 14.1* and *14.2*.

An indication of the combined effect of molybdenum and sulphur on the percentage of dietary copper which can be absorbed, is illustrated by the data in *Figure 14.4*, taken from a report by the Scottish Agricultural

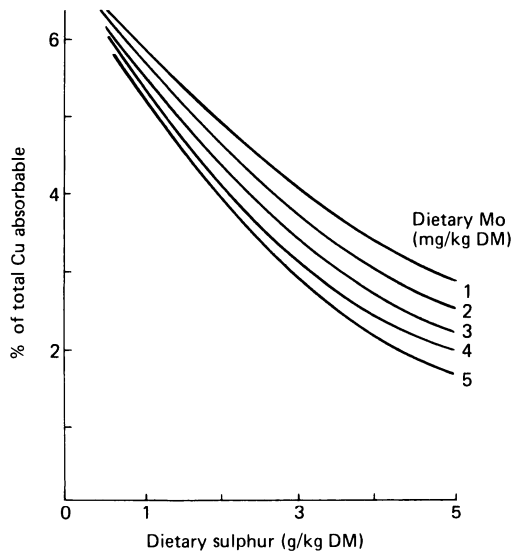

Figure 14.4 Predicted influence of dietary Mo (mg/kg DM) and dietary S (g/kg DM) upon absorbable copper. Data are derived from ADRA studies with Blackface sheep offered semi-synthetic diets and, provisionally, are regarded as appropriate for cattle maintained on similar diets. (Scottish Agricultural Colleges and Scottish Agricultural Research Institutes, 1982)

Colleges and Scottish Agricultural Research Institutes on Trace Element Deficiency in Ruminants (1982).

The resulting deficiency in copper in animals grazing forage from land which is either deficient in copper or contains a copper antagonist has a number of adverse effects on performance. These were itemized by MAFF (1982) to be as follows:

(1) molybdenosis—which results in hypocuprosis and leads to a persistent scour, stunted growth and depressed milk output;

(2) swayback in lambs;
(3) growth retardation in calves at intermediate soil molybdenum levels; this depression in growth can amount to about 20% and can be corrected by increasing the copper intake of the animal;
(4) growth retardation in lambs;
(5) infertility—while many authorities, particularly veterinary surgeons, link low copper availability with infertility, this factor has not been proved in controlled trials;
(6) anaemia;
(7) increased susceptibility in infection.

The final problem was clearly itemized in work carried out by Suttle (1982) at the Moredun Institute, the results of which are given in *Table 14.5*. These illustrate the relationship between low blood plasma copper and increased mortality in lambs. Diagnosis of the cause of this mortality

Table 14.5 BLOOD COPPER STATUS AND LAMB MORTALITY AT EIGHT WEEKS

Breed/type of sheep	*Plasma Cu* (mg/ℓ)	*Mortality* (%)
Low blood Cu line	0.06	16.7
High blood Cu line	0.31	7.3
Scottish Blackface	0.07	25.0
Welsh Mountain	0.29	2.5

(From Suttle, 1982)

showed many conditions, but was not identified as being typical swayback. The low plasma copper seems to be related to an inability of the lamb to withstand infection.

THE COST OF COPPER DEFICIENCY IN RUMINANTS IN ENGLAND AND WALES

MAFF (1982) have made tentative estimates of the financial losses from clinical copper deficiency in cattle and sheep, amounting to £3.6 m/year as a result of copper deficiency in cattle, £0.5 m/year from swayback in lambs and £0.84 m/year resulting from depressed growth rates in sheep. This total loss of nearly £5 m/year takes no account of the effect on performance of subclinical copper deficiency. According to MAFF (1982) in areas where the molybdenum content of the herbage is above 5 mg/kg, copper deficiency can occur in animals even when the copper content of the pasture is quite high. This situation is made worse by the presence of sulphur, when copper deficiency may occur with herbages containing only 1–4 mg/kg of molybdenum. The molybdenum uptake by the herbage also increases as the pH rises, so that as the pH of the soil rises from 4.5–5.5 the molybdenum content doubles; an increase in soil pH from 5.5–6.5 increases the molybdenum content by two- to fivefold; a further increase in soil pH from 6.5–7.5 again doubles the molybdenum uptake.

In a study by Thornton, Kershaw and Davies (1972), in the Nottingham/Staffordshire area, molybdenum soil levels were found to vary from 0.4–3.5 mg/kg and in herbage DM from 0.8–3.0 mg/kg. While there were

several cases of hypocuprosis, a survey of blood copper levels in animals showing no obvious signs of copper deficiency revealed a large number of hypocupraemic animals with blood copper levels of less than 6 μg copper/ml, injection of 100 mg of copper as Cu Ca EDTA gave increases of liveweight gain of between 10–70% when compared with untreated control animals.

THE EFFECT OF CHANGES IN HUSBANDRY TECHNIQUES

As the various soil conditions referred to above have existed for centuries, changes in husbandry techniques must be the reasons why the problem of copper deficiency seems to be getting worse. The MAFF report itemized the following changes which might have contributed to the increased incidence of copper deficiency problems.

(1) Reduction (6.5%) in grassland area from 7371 million ha in 1969 to 6889 million ha in 1980.
(2) Reduction (12.0%) in forage not grass area from 124 million ha in 1969 to 109 million ha in 1980.
(3) Increased use of nitrogenous fertilizer—between 1970 and 1979 + 48% on lays + 64% on permanent pasture.
(4) Decreased use of phosphate fertilizer—between 1970 and 1979, 34% on lays, 14% on permanent pasture.
(5) Grassland composition: increase in ryegrass, decrease in cocksfoot, timothy, fescues and clover.
(6) Increase in amount of silage: hay DM 1970: 6791000 tonnes; 1977: 7378000 tonnes; silage DM 1970: 1702000 tonnes; 1977: 5502000 tonnes; silage as % of total 1970: 20%; 1977: 43%.
(7) Hill land improvement: 100000 ha in Wales in last 30 years.
(8) Increased average milk yield 1969–70: 3755 ℓ; 1977–1978: 4630 ℓ.
(9) Increased number of sheep 1970: 17620000; 1980: 22501000.
(10) Breed changes in both cattle and sheep.

Various authorities have presented data indicating the reasons why some of these changes in husbandry techniques have led to lower blood copper levels.

COPPER ABSORPTION BY AND FROM DIFFERENT PLANTS

Data from various authors (*Table 14.6*) show that legumes extract more copper from the soil than do grasses and thus the move away from these species towards ryegrass lays means that the amount of copper supplied to the animal has been reduced. On low copper soils there is, however, little difference to be found in the copper content of grass and legumes. Workers in both England and Wales have found levels of 2–4 mg/kg DM in both grass and legumes in low copper soils (MAFF, 1982). A number of workers have shown that the effect of copper fertilizer also varies between grass and legumes, particularly after the first defoliation. Mitchell, Reith and Johnson (1957) showed that the copper level of grass increased by only

Table 14.6 COPPER (mg/kg DM) IN PLANT TISSUES

Grass	4.0–9.0	(MAFF, 1982)
Ryegrass	5.8–6.4	(Whitehead, 1966)
	6.0	(Davey, 1957)
Cocksfoot	7.6	(Davey, 1957)
	5.4–6.2	(Whitehead, 1966)
Lucerne	10.1–12.2	(Whitehead, 1966)
Red clover	15.5	(Flemming, 1963)
	11.7	(Davey, 1957)

Table 14.7 COPPER CONTENT OF FIRST CUT HERBAGE GROWN IN SOIL IN WHICH SLURRY 750 m^3/ha HAD BEEN INCORPORATED TO A DEPTH OF 10 cm

Plant genotype	*Control*	*Treatment*
	Copper content (IU/g)	*of herbage*
Lolium perenne, S23	11.0	16.4***
Lolium perenne, Vigor	11.3	16.9***
Lolium perenne, Reveille	13.8	17.6***
Lolium multiflorum, Lemtal	11.8	15.6***
Festuca arundinacea, Alta	10.0	18.0***
Dactylis glomerata, Rano	16.8	25.8***
Phleum pratense, Climax	13.7	23.3***
Trifolium repens, Blanca	10.7	11.9 NS
Trifolium pratense, Hungaropoly	9.5	13.5***
Trifolium repens, Kentish wild white	12.0	11.9 NS

(From McGrath, 1981)
***Significantly different from control at $P \leq 0.001$
NS, not significant

Table 14.8 ESTIMATE OF COPPER ABSORPTION BY SCOTTISH BLACKFACE EWES FROM NATURAL FOODSTUFFS OF LOW MOLYBDENUM CONTENT (LESS THAN 2 mg/kg DM)

	% total Cu absorbable	*No. of estimates*
Grazed herbage—July	2.5	7
Grazed herbage—Sept/Oct	1.4	6
Silage	4.9	7
Hay	7.3	5
Root brassicas	6.7	2
Cereals	9.1	3
Leafy brassicas	12.8	5

(From Scottish Agricultural Colleges and Research Institutes, 1982)

1.3-fold, whilst that of red clover increased by sixfold from the same rate of copper fertilizer. HFRO (1979) reported a twofold increase in the copper content of ryegrass as opposed to a threefold increase in white clover.

Similar effects were reported at the Bordeaux conference by McGrath (1981), data from which are illustrated in *Table 14.7*.

As well as an apparent difference in the amount of copper which different plants can absorb from the soil, data presented in the report of the Scottish Agricultural Colleges and Research Institutes on Trace Element Deficiency in Ruminants (1982), illustrated that animals also absorb copper at a different rate from different plants (*Table 14.8*).

These differences of absorption, by both plants and animals, led MAFF to conclude that 'The wide variation in copper absorbability between and within foodstuffs means that copper concentration *per se* may be of little nutritional significance'.

THE EFFECT OF HILL LAND IMPROVEMENT

A further factor which affects the availability of copper in the herbage is hill land improvement. Data from the Scottish Agricultural Colleges and

Table 14.9 EFFECT OF HILL LAND IMPROVEMENT ON COPPER, SULPHUR AND MOLYBDENUM LEVELS IN HERBAGE

Harvest date	*Cu* (mg/kg)		*S* (g/kg)		*Mo* (mg/kg)	
	Improved	*Unimproved*	*Improved*	*Unimproved*	*Improved*	*Unimproved*
29 May	6.3	6.8	5.2	1.8	3.9	0.9
18 July	4.5	5.5	2.6	1.8	2.3	0.8
13 August	4.0	4.8	3.2	1.7	4.0	0.9

(From Scottish Agricultural Colleges and Research Institutes, 1982)

Research Institutes (1982), shown in *Table 14.9*, clearly demonstrate the higher molybdenum and sulphur content of herbage after land improvement. These higher levels of copper antagonists reduce copper absorption and utilization by the animal grazing the herbage.

THE EFFECT OF BREED

At least in sheep, and possibly in other species, breed can have a very marked effect on copper absorption. Work by Wooliams *et al.* (1982) shown in *Tables 14.10* and *14.11* clearly demonstrated that the Blackface sheep retains less of its ingested copper than do other breeds.

The Texel × Blackface showed a copper retention more than double that of the Pure Blackface and thus this breed is much more likely to suffer from copper toxicity, while the Blackface is much more likely to suffer from copper deficiency.

Thus the effect of soil copper level, soil and herbage copper antagonist

Tabel 14.10 EFFECT ON BREED OF SIRE ON COPPER ACCUMULATION IN LIVER OF LAMBS

Sire breed	*Dietary Cu conc.* (mg/kg DM)		*Proportion of dietary Cu retained in liver*
	12	*20*	
	Liver Cu conc. (mg/kg DM) *after 13 weeks*		
Blackface	292	567	0.056
East Friesland	470	754	0.067
Finnish Landrace	409	767	0.086
Suffolk	615	1116	0.073
Texel	695	1492	0.137

(From Wooliams *et al.*, 1982)

Table 14.11 EFFECT ON BREED ON BLOOD PLASMA COPPER CONCENTRATION

Breed	*mg Cu in dietary DM*	*Cu conc. in blood plasma* (mg/ℓ)
Blackface × Blackface	4	0.61
Blackface × Welsh	4	0.86
Welsh × Welsh	4	0.91
Mean of above breeds	4	0.80
at different dietary	9	0.89
copper concentrations	17	0.92
	29	0.85

(From Wooliams *et al.*, 1982)

levels, husbandry systems and breed of animal must make highly questionable the EEC approach of laying down a maximum level of 20 mg of copper/kg. This would mean that many samples of feed would contain a few mg/kg of copper only. It would appear to be impossible for the authorities to lay down a single level for the UK, let alone for the whole of Europe. To penalize the pig farmer in order to protect the sheep farmer from copper toxicity seems to be unrealistic.

The economic effect of the use of copper in pig feeds

From the conclusions of the Bordeaux Conference and the above discussion, one might conclude that 200 mg of copper/kg of pig feed was quite acceptable. Nonetheless, the EEC has decided in its wisdom to cut the maximum allowed level to 125 mg of copper/kg from four months of age.

It is common practice within the UK to keep pigs from about eight to ten weeks of age through to slaughter in one house, with a single bulk feeding system. Faced with a reduction from 200 to 125 mg of copper/kg in the pig feed at 17 weeks, the farmer must either build new housing, duplicate his feeding system or feed 125 mg copper/kg throughout the growing phase. Based on data prepared by UKASTA which was reported to the Bordeaux Conference (Cooke, 1981) and illustrated in part in *Figure 14.5*, this recent

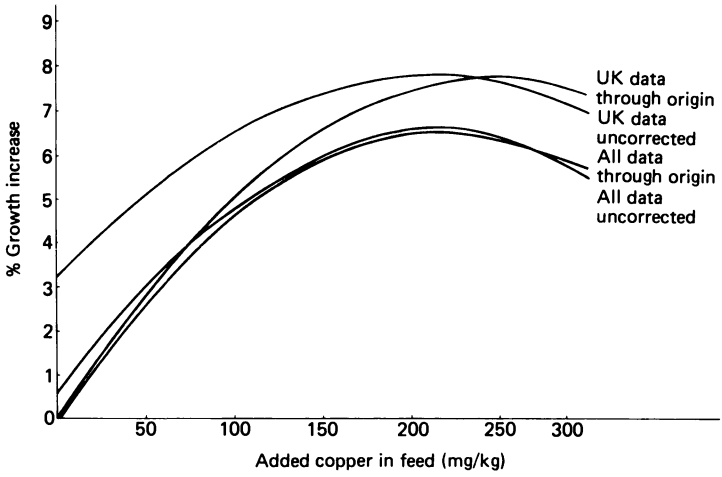

Figure 14.5 Growth response of pigs to copper in feed (Cooke, 1981)

change in the Annex II entry will cost the UK pig producer over £1 000000/year in lost performance and £4 700 000/year in depreciation and interest charges on the cost of modifying buildings or feeding equipment to enable a lower level of copper to be fed to pigs over four months of age.

Even having imposed this reduction in copper use, it is understood that pressure still exists within the EEC for a further reduction to a maximum of 125 mg of copper/kg for all pigs and a number of options are currently under study with a view to further changes to the Annex II entry being proposed before November 1983. These options are summarized in *Table 14.12*.

Table 14.12 FUTURE OPTIONS FOR COPPER IN PIG FEEDS CURRENTLY UNDER CONSIDERATION BY THE EEC

Option	*Max. Cu content of feeds* (mg/kg)
Position up to June 1982	200 for all pig feeds
Current position	200 to 4 months, 125 thereafter
Annex 1 entry	125 for all pig feeds
Option A	200 to 13 weeks, 100 13–26 weeks, 50 thereafter
Option B	200 to 16 weeks, 125 16–26 weeks, 50 thereafter
Option C	200 to 17 weeks, 50 thereafter
Option D	155 to 26 weeks, 40 thereafter

Table 14.13 EFFECT OF DIFFERENT MAXIMUM COPPER OPTIONS ON UK COPPER USAGE AND ECONOMIES OF PIG PRODUCTION

Option	*Tonnage of Cu fed/year*	*Economic effect compared to Annex 1 entry*		
		on performance (£)	*on cost/year for depr. and interest* (£)	*total/year* (£)
Annex 1	562.0	Nil	Nil	Nil
A	520.6	Nil	6353600	−6353600
B	635.8	+12237033	4765200	+7471833
C	593.4	+6722109	4765200	+1956909
D	562.0	+4765200	Nil	+4765200

As well as the current position, Options A, B and C would all require modifications to buildings or feeding equipment. Based on current UK pig numbers and the amount of copper used in pig feeds the economic effects of the various options can be calculated from response data in the UKASTA (1978) survey on 'the responses to copper by growing pigs'. The results of these calculations are shown in *Table 14.13*.

While one must seriously question the need to reduce the level of copper entering the environment via pig slurry, it can be seen from the data in *Table 14.13* that Option A would give a lower amount of copper than the current Annex I level but at a cost of in excess of £6000000/year to the pig producers in the UK. While Options B and C would give a higher return than a standard 125 mg/kg, this would be at the expense of a higher level of copper entering the environment. Option D, which would allow 155 mg/kg through to 26 weeks and 40 mg/kg thereafter would give the same amount of copper as the current Annex I entry but over £4760000 higher return to

Table 14.14 EEC PIG SLAUGHTER DATA AND ESTIMATED FEED USAGE

	Av. 1980 carcase wt (kg) (Weir, 1982)	*Live wt equivalent* (kg)	*Slaughterings ('000 head) in 1980*	*Assumed fcr*	*Est*[a] *feed used* ('000 t)	*Est*[b] *no. sows and boars* ('000 head)	*Est*[c] *sows feed* ('000 t)
West Germany	85	106	37998	3.2	12221	2505	3006
France	88	110	21109	3.2	7066	1392	1670
Belgium	81	101	8267	3.2	2523	545	654
Netherlands	85	106	13239	3.2	4258	873	1047
Denmark	67	87	14483	2.8	3285	904	1085
Ireland	66	86	2361	2.8	528	147	177
UK	64	83	15487[d]	2.8	3335	967	1160
Italy	106	128	10285	3.5	4430	718	861

[a] Assuming number of slaughter pigs is increased by 2.5% to cover replacement breeders
[b] Assuming 19 slaughter or replacement breeders of 80–90 kg/sow/year
18 slaughter or replacement breeders of 100–110 kg/sow/year
17 slaughter or replacement breeders of 120 kg+/sow/year
and UK data that shows that sows make up 86.4% of breeding herd
[c] Assuming 1.2 tonnes/sow/year
[d] 1981 estimate

Table 14.15 EFFECT OF VARIOUS OPTIONS ON COPPER LEVELS ON COPPER USAGE IN EEC COUNTRIES (TONNES COPPER/YEAR)

	Annex I 125 mg/kg in all pig feeds	*Option D 155 mg/kg to 26 weeks 40 mg/kg over 26 weeks*	*UKASTA suggestion 150 mg/kg to 26 weeks 35 mg/kg over 26 weeks*
West Germany	1903	2014	1937
France	1092	1162	1118
Belgium	397	417	401
Netherlands	663	701	675
Denmark	546	552	531
Ireland	88	88	85
UK	562	563	540
Italy	661	721	694
EEC Total	5912	6218	5981
% Change from Annex I	—	5	1

Table 14.16 ECONOMIC EFFECT OF VARIOUS OPTIONS ON COPPER LEVELS IN PIG FEEDS IN THE EEC

	Annex I 125 mg/kg in all pig feeds	*Option D 155 mg/kg to 26 weeks 40 mg/kg over 26 wks*	*UKASTA suggestion 150 mg/kg to 26 weeks 35 mg/kg over 26 wks*
Added copper (mg/kg)	110	140	135
Growth response over EEC average gain of			
96 kg (%)	4.9	5.6	5.5
(kg/pig)	4.7	5.4	5.3
Value/pig at 80p/kg compared to Annex I	Nil	£0.56	£0.48
Value to EEC pig industry/year compared with Annex I	Nil	£69008240	£59149920

(Based on UKASTA, 1978)

the pig producers each year. This extra return would be obtained from the growth response to the extra copper given to the growing pig, while this extra copper usage is balanced by the reduced amount given to the breeding herd where there is not evidence of a positive response to copper.

Based on the EEC pig slaughter data shown in *Table 14.14*, Option D can be evaluated in terms of its environmental impact throughout Europe, compared to the Annex I entry (*Table 14.15*). This indicates that because of higher slaughter weights in a number of EEC member states, compared with the UK, Option D would increase the amount of copper entering the environment to a level some 5% higher than would be obtained by the use of 125 mg of copper/kg in all pig feeds as currently allowed in Annex I. A modification of Option D, reducing the maximum copper to 150 mg/kg up to 26 weeks and 35 mg/kg over 26 weeks, would lead to a very similar environmental deposition of copper to that of 125 mg/kg but with an extra return to the EEC pig industry in excess of £59000000/year (*Table 14.16*). This suggestion from UKASTA appears to offer the best opportunity of maximizing the return from the use of copper in pig feeds, while minimizing the environmental impact.

In conclusion, the EEC policy on legislating for copper in animal feeds must be seriously questioned. While one must be concerned by long-term effects on the environment from the use of any nutrient in animal feeds, the availability of copper is so much influenced by soil copper status and antagonists to copper absorption by livestock that a universal policy throughout the EEC cannot make nutritional sense. It appears unlikely that the use of pig slurry containing high levels of copper will lead to any significant increase of copper toxicity in sheep due to the fact that copper levels in soil tend to be on the deficient side rather than excessive, and absorption of copper by the plant and thus transferred to the animal is extremely poor. Thus, while it is unlikely that the use of copper containing pig slurry will solve copper deficiency problems in bovines, it certainly should not lead to toxic problems.

The nutritionists' first responsibility must be to ensure that livestock are correctly fed and the weight of evidence suggests that there is a much larger problem of copper deficiency than copper toxicity in ruminant animals. Indeed, within England and Wales, this deficiency is costing the farming community in excess of £5 000 000/annum, yet the EEC wants to impose additional reduction on copper in pig feeds, which will further reduce returns to British and European farmers.

In this context, it is interesting to note that the fifth feed surveillance paper from the Ministry of Agriculture, Fisheries and Food in the UK states that the most significant single dietary source of copper to the human being is meat offals and that the estimated average copper intake is less than 1.8 mg/head/day which is less than the 2 mg/day considered by the World Health Organization to be the human requirement. The proposed action by the EEC will further restrict the intake of copper to the detriment of the human population.

The problem of nutrient requirements should, in my opinion and that of many of my colleagues, be left to the animal nutritionists of each member state. The drive for harmonization throughout Europe must be seriously questioned due to the wide variation in husbandry systems, stocking density, climate, topography and herbage copper availability which exists throughout the community.

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INDEX

Erratum slip

Recent Advances in Animal Nutrition – 1983

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The first three sentences on page 184 should read:

The quantity of hay made in the early 1970s remained fairly stable at 8.5 million tonnes but this figure declined to an estimated 6.9 million tonnes in 1980. Silage, on the other hand has increased substantially. Nearly 8 million tonnes of grass silage were harvested in 1969 but by 1980 this figure had more than trebled to an estimated 28 million tonnes (Burns, Lewis and Randall, 1982).