HGCA

RESEARCH REVIEW No. 24

NUTRITIONAL ASPECTS OF CEREALS, CEREAL GRAIN BY-PRODUCTS AND CEREAL STRAW FOR RUMINANTS

MARCH 1993

Price £20.00

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NUTRITIONAL ASPECTS OF CEREALS, CEREAL GRAIN BY-PRODUCTS AND CEREAL STRAW FOR RUMINANTS

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ABSTRACT

Nutritional aspects of cereal grains, cereal by-products and cereal straws for ruminants are reviewed in three self-contained sections. Recommendations for research are given at the end of each section.

For cereal grains, the review covers the quantities of cereals used for ruminant feeding, structure, composition of and processes of digestion in the animal. The influence of processing on digestion is examined. The review also examines the energy and protein value of cereal grains, factors affecting these values and effects of cereals in mixed diets.

The findings of the review highlight the dearth of information on factors influencing the energy and protein value of cereal grains and for protein value in particular, further work on measurement techniques is required. The interaction of cereal grains with other dietary ingredients, particularly grass silage, warrants further study.

For cereal by-products, the nature and source of the wide range available for ruminant feeding is reviewed, together with their composition, nutritive value and use in diets. For many by-products only limited amounts of recent information are available on their energy and protein values and, for dried distillery and brewery by-products in particular, there are doubts about the validity of current methods for assessing protein quality. Many by-products can be successfully used in animal production systems although some oil-rich by-products can prevent optimal digestion in the rumen. Further work is required to develop means of alleviating these effects.

For cereal straw, the review covers the quantities available for feeding, anatomical structure, chemical composition and digestion. The currently available data on the digestibility and energy value of straw are reviewed

along with the influence of these and other factors on voluntary intake. The important influence of the proportions of the different botanical fractions (e.g. leaves, stems) on the energy and protein value is highlighted as is the lack of information on the factors such as geographical location, fertiliser treatment and fungal disease on the nutritive value of straw.

The review confirms the need for further work on the laboratory evaluation of straws together with the study of new, environmentally friendly methods of upgrading nutritive value.

This review completed in Febrary 1993 and with 180 pages in the full article, was funded by the HOME-GROWN CEREALS AUTHORITY, Hamlyn House, Highgate Hill, London N19 5PR, from whom copies may be obtained at a price of £20.00 each (including postage and packaging).

SUMMARY OF RECOMMENDATIONS FOR RESEARCH

1. Cereal grains

Very high priority

i. Study the factors influencing the measurement of dry matter, starch and protein degradation in the rumen using the nylon bag method.

ii. Determine the influence of factors such as protein content and processing/treatment methods on rate of cereal protein and starch degradation in the rumen.

iii. Study the influence of variety within cereal species on the rate and extent of starch and protein degradation in the rumen.

iv. Investigate treatments and processing methods for their ability to manipulate the rate and extent of starch and protein degradation in the rumen.

v. Study the effect of low rates of cereal supplementation to grass silage-based diets on ration digestion in the rumen, rumen metabolism and animal production.

High priority

i. Define the influence of agronomic factors such as fertiliser use on cereal protein content and quality for ruminants.

ii. Undertake animal production and metabolism studies into the use of high rates of cereals in diets for dairy cows and growing cattle. Emphasis should initially be put on the use of wheat.

Moderately high priority

i. Investigate the effects of grain treatments such as sodium hydroxide on grass silage intake, milk production and rumen metabolism.

ii. Investigate the effect of diets containing cereals of high oil content (oats and naked oats) on digestion in the rumen, rumen metabolism and the fatty acid composition of milk and body fat.

iii. Further measurements in vivo of the ME contents of cereals including those of low specific weights, and the development of accurate and rapid laboratory methods for predicting ME content.

2. Cereal by-products

Very high priority

i. Develop rapid laboratory procedures for estimating the energy value of different cereal by-products.

ii. Establish protein degradability in animals, including a study into the validity of current techniques for estimating nitrogen degradability and unavailable nitrogen in dried distillery and brewery by-products.

iii. Develop laboratory procedures to predict more accurately protein quality of different by-products.

High priority

i. For brewery and distillery by-products containing high concentrations of unsaturated oils, further elucidate the relationship between divalent cation supplementation, rumen function and methanogenesis.

ii. Study the influence of the unsaturated oil content of distillery and brewery by-products on milk composition in dairy cows and carcass quality and fat composition in cattle and sheep.

iii. Study the effect of the lactic acid present in wet brewery and distillery products on the rumen environment and any interaction with the amounts and type of other feeds in the diet, particularly grass silage.

Moderately high priority

i. Further study the use of cereal by-products as silage absorbents/inoculants.

ii. On completion of the very high and high priorities, evaluate these by-products in animal production systems.

3. Cereal straws

Very high priority

i. Study the effects of geographical location, year, fertiliser application, fungal disease and cereal variety on nutritional quality of straws.

ii. Determine the relationships between the quality of straw stems and leaves and the possibilities for fractionation.

iii. Examine the role of plant breeding in influencing straw quality.

iv. Undertake a comparison of digestibility and rumen degradability measurements (in vivo and in vitro) for predicting straw intake and animal performance.

High priority

i. Undertake the development of in vitro and other labaoratory methods for predicting degradability characteristics.

ii. Study the influence of selectivity of animals on straw and energy intake.

iii. Examine the influence of type of supplement on the intake and rumen digestion of straws and microbial protein synthesis in the rumen.

Moderately high priority

i. Investigate the factors influencing the utilisation of nitrogen in ammonia/urea treated straws.

ii. Develop an efficient and environmentally friendly means of upgrading straws, e.g., use of enzyme preparations.

GLOSSARY OF TERMS

acidosis	a condition where the rumen pH is too low
'a' fraction	fraction of a feedstuff immediately soluble in the rumen
'b' fraction	fraction of a feedstuff not soluble in the rumen but potentially degradable
birefringence	refraction of polarised light
buffer feed	a feed offered to supplement limited grazing
'c'	rate of degradation of a feedstuff in the rumen
cannulated	the result of the surgical introduction of a tube into part of the digestive tract
cellulose	a fraction of plant cell walls
cellulolysis	the fermentation of cellulose by rumen micro-organisms
degradability	extent to which a feedstuff or a fraction thereof is broken down by microbial action in the rumen
digestion	processes of breaking down feedstuffs throughout the whole digestive tract
digestibility	extent to which a feedstuff or a fraction thereof is broken down in the whole digestive tract.
digestible energy	energy provided by a feedstuff minus the energy lost in faeces
DOMD	the proportion of the organic matter in the feedstuff dry matter which is apparently digested through the whole digestive tract

eructation	the reflux action which allows gas in the rumen to be released into the mouth and hence to the atmosphere
gross energy	maximum amount of energy in a feedstuff as released on complete combustion
hemicellulose	a fraction of plant cell walls
in sacco	in nylon bags
in vitro	literally in glass, i.e. in a laboratory procedure
in vivo	in an animal
keratosis	the result of damage to the rumen wall caused by digestive malfunction
metabolisable energy	energy provided by a feedstuff minus the energy lost in faeces, urine and as methane gas
methanogenesis	production of methane gas in the rumen as a result of microbial activity
neutral detergent fibre	fraction of a feedstuff insoluble in neutral detergent solution and representing a measure of its cell wall content
rancidity	the result of certain chemical changes in an oil or fat
rumenitis	a condition characterised by damage to the rumen epithelia caused by acidosis
RUSITEC	an artificial rumen established in the laboratory
stomata	small pores in leaves of plants
straight feeding-stuff	a non-forage feedingstuff that can be fed without further processing or supplementation

volatile fatty acids	acids produced in the rumen as a result of microbial breakdown of feedstuffs

LIST OF ABBREVIATIONS

ADF	acid detergent fibre
ADIN	acid detergent insoluble nitrogen
ADL	acid detergent lignin
AO	Aspergillus oryzae
ATP	Adenosine triphosphate
BFA	branched chain fatty acid
CF	crude fibre
CP	crude protein
DDG	distillers' dark grains
DE	digestible energy
DM	dry matter
DMI	dry matter intake
DOMD	digestible organic matter in the dry matter
EC	European Community
Ed	Editor
ESW	evaporated spent wash
g	gram
GE	gross energy
h	hour
kg	kilogram
LW	live weight
LWG	liveweight gain
MAFF	Ministry of Agriculture, Fisheries and Food
ME	metabolisable energy
mg	milligram
MGF	maize gluten feed
min	minute
MJ	megajoule(s)

N	nitrogen
NAN	non-ammonia nitrogen
NDF	neutral detergent fibre
NOSCA	North of Scotland College of Agriculture (now SAC, Aberdeen)
OM	organic matter
OMD	organic matter digestibility
OMDR	organic matter apparently digested in the rumen
OMF	organic matter fermented
PAS	pot ale syrup
t	tonne(s)
UK	United Kingdom
UKASTA	United Kingdom Agricultural Supply Trade Association
VFA	volatile fatty acid

SECTION 1

CEREAL GRAINS

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1.0 QUANTITIES OF CEREALS USED

The animal feed sector represents the single largest market for grain in the UK. In 1991/92, it is forecast that the animal feed sector will use 8.9 million tonnes (t) of cereals, accounting for 40% of UK cereal production (HGCA, 1992).

In 1990/91, it was estimated that 9.15 million t of grain were consumed by livestock. This includes that used by the compound feed industry, by pigs and poultry, and that fed directly on-farm. This total comprised some 4.8 million t wheat (52%), 3.9 million t barley (42%) and 0.5 million t of other cereals (6%). Estimated details of wheat and barley use for 1990/91 are given in Table 1.

Table 1. UK animal feed use (x 10^3 t) in 1990/91 (after MAFF, 1991).

	Wheat	Barley
Recorded use:		
Compounders	2917	798
England and Wales, fed on farm	629	1827
Scotland, fed on farm	34	486
Unrecorded use	1194	753
Total: MAFF estimates	4774	3864

Some information on amounts of cereals fed to different livestock classes is available (MAFF, 1991), but this is restricted to cereals fed directly on farms. Details for 1990/91, for farms in England and Wales, are shown in Table 2.

Table 2. Cereal grains fed to different livestock classes (after MAFF, 1991).

	Cattle	Pigs	Poultry	Other	TOTAL
Quantity (x 10^3 t)	1541	780	127	177	2625
% of total	59	30	5	6	100

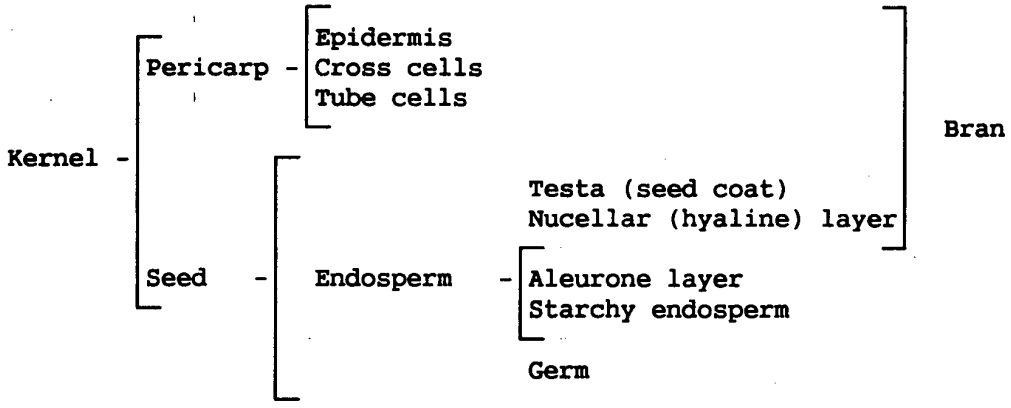
It must be emphasised that this applies only to cereals fed directly on farms in England and Wales, which contributed 2.6 million t (28%) out of 9.15 million t used by the whole livestock industry in 1990/91.

2.0 STRUCTURE AND COMPOSITION OF GRAIN

2.1 Introduction

Cereal grains develop from the ovary and ovule of the cereal flowers following fertilisation. The cereal grain is composed of the seed, the pericarp (seed coat), and also in the case of barley (Hordeum sativum) and oats (Avena sativa), also the husk. The husk is composed of the two scale-like structures (palea and lemma), collectively known as glumes, which surround the grain. In barley the glumes fuse with the outer coating of the developing grain and produce a covered kernel, or 'closed grain'. In contrast, the glumes in wheat (Triticum aestivum) are associated only loosely with the grain and are easily separated during threshing. The development of the oat grain lies between those of wheat and barley with the glumes adhering to, rather than fusing with, the grain during development. The presence or absence of this protective envelope around the grain influences its chemical composition and nutritional value. The structure of cereal grains is illustrated in Figure 1.

Figure 1. Outline of the components of cereal grain (after Kent, 1975).



The proportions of the individual components of the grains of barley, wheat and oats are given in Table 3. Starchy endosperm represents the largest proportion of the grain in all cereal types, ranging from 0.82 for wheat to 0.63 for oats, while the germ represents the smallest portion (0.03-0.04 for all cereal types). The husk and bran fraction comprise the remaining portion of the grain.

Table 3. Proportions of the component parts of grain found in wheat, barley and oats (after Kent, 1975).

	Wheat	Barley	Oats
Husk	0	0.13	0.25
Bran	0.15	0.08	0.09
Starchy endosperm	0.82	0.76	0.63
Germ	0.04	0.03	0.03

2.2 Distribution of nutrients in the grain

Nutrients are not uniformly distributed between the various components of the grain, either within or between species (Finlayson, 1989). The distribution of protein and lipid in wheat is illustrated in Table 4. Data on the chemical composition of barley, wheat and oats have been compiled by MAFF (1990).

Table 4. Distribution of protein and lipid in wheat present in the main morphological parts (Data from Hinton, 1952 reported by Kent, 1975).

	Protein	Lipid
Bran	0.20	0.30
Endosperm	0.72	0.50
Germ	0.08	0.20

2.3 Carbohydrate content of cereal grains

The typical carbohydrate content of cereal grains is presented in Table 5 and contrasted with temperate grasses. Hemicellulose is the main structural polysaccharide in cereal grain comprising 70-150 g kg^{-1} dry matter (DM), with cellulose comprising only a small proportion (20-50 g kg^{-1} DM) of the grain. In contrast, storage polysaccharides (principally starch) comprise approximately 800 g kg^{-1} DM. The composition of grasses is notably different

from cereal grains, grasses being rich in cellulose but with negligible amounts of starch.

Table 5. Carbohydrate content (g kg^{-1} DM) of temperate grasses and cereal grain (after Van Soest, 1982).

Component	Temperate grasses	Cereal grain
Sugars	100	negligible
Fructosans	10-250	0
Starch	0	800
Pectins	10-20	negligible
Cellulose	200-400	20-50
Hemicellulose	150-250	70-150

2.3.1 Starch

Starch is found almost exclusively in the endosperm. The starchy endosperm is composed of microscopic starch granules bound closely together. The starch grains within the endosperm are arranged in layers, which consist of crystalline regions extending radially from the centre of the grain, and are embedded in a protein matrix surrounded by thin cell walls.

The starch is a mixture of two types of polymer, amylose and amylopectin. Amylose is an α -1,4 linked D-glucose straight chain polymer containing 1000-2000 glucose units, and amylopectin is a highly branched polymer comprising 20-25 D-glucose units (α-1,4 linked) and joined at branch points by α -1,6 linked D-glucose molecules. The ratio of amylose to amylopectin is genetically controlled, but plant maturity increases the ratio. The amylose contents of the starch in barley, wheat and oats are shown in Table 6.

Starch granule quality is influenced by starch type. 'Floury' endosperm contains a high proportion of amylose, while 'flinty' endosperm is associated with amylopectin. It is the strength and cohesion of the starch granules

within the protein matrix and cell walls, which account for the hardness of cereal grains.

Table 6. The proportion of amylose and the gelatinisation temperature range of starch in barley, wheat and oats (after Armstrong, 1972).

	Barley	Wheat	Oats
Amylose in starch	0.22	0.26	0.27
Gelatinisation temperature range (°C)	59-64	65-67	NQ

NQ = Not quoted.

Grain 'hardness' (expressed in terms of grain milling energy) is negatively correlated with the amounts of nitrogen that can be solubilised, and the degradation of the cell walls (Camm et al., 1990). The structure of the starch granule is disrupted by both temperature and water. The temperature at which the crystalline structure and birefringence properties are lost is referred to as the gelatinisation temperature. Gelatinisation temperature increases with the proportion of amylose in the starch (Table 6).

2.3.2 Cell wall composition

The cell wall content (measured as neutral detergent fibre) of cereal grains typically ranges from 124 for wheat to 310 g kg^{-1} DM for oats (MAFF, 1990). The highest proportion of fibre is contained in the bran fraction of the grain; for example, the cell wall content of wheat bran is approximately 480 g kg^{-1} DM (MAFF, 1990).

Comparison of the cell walls surrounding the starch granules in the starchy endosperm and those in the aleurone layer has revealed differences in their composition. These differences in the cellulose and hemicellulose composition of endosperm and aleurone cell walls are illustrated in Table 7.

Table 7. The cellulose and hemicellulose composition (proportion of the cell walls) of endosperm and aleurone cell walls (after Fuller and Chesson, 1992).

Cereal	Cell wall type	Hemicellulose		Cellulose
		Mixed linked glucans	Arabinoxylans	
Barley	Starchy endosperm	0.70	0.20	0.02
	Aleurone layer	0.26	0.67	0.02
Wheat	Starchy endosperm	0.20	0.70	0.04
	Aleurone layer	0.29	0.65	0.02

A high proportion of the cell walls of wheat and barley aleurone cells and wheat endosperm cells consist of the pentosan, arabinoxylan. In contrast, barley starchy endosperm cell walls consist mainly of soluble ß-glucan. A common feature of both types of cell wall is their high hydration capacity, giving them the ability to bind up to ten times their own weight of water, which can increase the viscosity of the gut contents. The importance of ß-glucans and arabinoxylans on the dynamics of rumen fermentation and the rate of starch and protein degradation in the rumen is not known. Both types of cell wall have a low cellulose content (20-40 g kg^{-1} of the cell wall DM). While a high proportion of the cellulose is digested in the rumen, a substantial proportion of hemicellulose escapes the rumen to be fermented lower down the tract (Van Soest, 1982). Data from Beever *et al.* (1972) indicate that 830-860 g kg^{-1} of the dietary hemicellulose were digested in the rumen of sheep receiving either *ad libitum* hay or restricted grass diets. The remaining portion of the hemicellulose were digested in either the small intestine, or in the caecum and colon. The reasons for the escape of some hemicellulose from rumen fermentation and the nutritional importance of this are not clear.

3.0 DIGESTIVE PROCESSES AND RUMEN FERMENTATION

The fundamental effects of feeding cereals to ruminants need to be considered prior to any discussion of cereals in diets.

3.1 Ruminant digestion

The ruminant's unique digestive system is well described in many good text

books (e.g. Church, 1975). Microbial fermentation in the reticulo-rumen results in important changes to all the major nutrients. Most carbohydrates are fermented to volatile fatty acids (VFAs) but a variable proportion escape fermentation to be digested as glucose in the abomasum or duodenum. Feed proteins are either degraded in the rumen or escape degradation to pass into the abomasum and duodenum. The synchronisation between energy for microbial growth and nitrogen release from feeds in the reticulo-rumen is very important in determining the amount of microbial protein synthesis (Armstrong and Finlayson, 1992).

The importance of form of carbohydrates in ruminant diets was first recognised when Powell (1938) reported on the effects of dietary roughage on milk production. It was subsequently found that the type of rumen fermentation, particularly the ratio of volatile fatty acids (VFA) acetic, propionic and butyric was fundamentally important (Phillipson and McAnally, 1942). Cereals and other carbohydrate sources can have significant effects on rumen pH and VFA production, and on starch supply to the small intestine. Important factors determining the rate and extent of starch fermentation and hence rumen pH include cereal type, processing method, amounts of carbohydrates fed, feeding frequency and basal diet.

The optimum rumen pH for fermentation of cellulose is generally accepted to be in the range 6.2-6.7 and it is increasingly impaired below 6.2 (Halliwell, 1957). At pH 5.5 or less, acidosis occurs due to the accumulation of lactic acid in the rumen so that animals lose their appetites. The addition of large amounts of starch to diets is a major cause of depressed cellulolysis (Balch and Johnson, 1950; Head, 1953; El Shazly et al., 1961; Campling and Murdoch, 1966). However, the rate of fermentation of starch, which is especially affected by the method of processing, is also very important (Ørskov and Fraser, 1975). The amount of supplementary carbohydrate fed is also important, since small amounts may have little if any effect on cellulolysis, but may give benefits such as increased microbial protein synthesis (Thomas et al., 1980). Another important effect is that increased amounts of starch-rich concentrates in the diet reduce the time spent eating and ruminating, so that saliva production is reduced (Webster, 1987). This is significant because saliva contains large amounts of sodium bicarbonate and phosphates which buffer the acids naturally produced during rumen fermentation. Frequency of feeding is also important as increased frequency tends to minimise variation in rumen pH (Mould, 1988).

3.2 Effect of cereal species

There are known to be marked differences between barley and maize in the extent of starch digestion in the rumen. Armstrong (1974) reported that 94% and 74% of the starch was digested in the rumen with rolled barley and cracked or ground maize respectively. Sutton et al. (1980) in studies with dairy cows, reported that the flow of starch to the duodenum was almost trebled (1.22 compared with 0.45 kg day^{-1}) when ground maize was fed compared with rolled barley, in a diet consisting of 60% concentrates: 40% hay in the DM. Perhaps surprisingly, differences in the molar proportions of rumen VFAs were only small between the two diets. In a review of starch utilisation by ruminants, Waldo (1973) reported that 94% of barley starch was degraded before the abomasum, compared with 78% and 76% of maize and sorghum starch respectively.

Rumen degradability of the DM of rolled barley, wheat and oats was examined by Moran (1986) and the data fitted to the exponential equation of Ørskov and McDonald (1979):

$$P = a + b\,(1-e^{-ct})$$

where P = DM digested in the rumen at time t
a = immediately soluble fraction
b = insoluble but potentially digestible fraction
c = rate of digestion of b

These data are shown in Table 8.

Table 8. Degradability characteristics of cereals incubated in the rumen of cows (g kg^{-1} DM incubated or as stated) (after Moran, 1986).

Degradation characteristic	Cereal			
	Barley	Wheat	Oats	SED
Potentially degradable (a+b)	928^{x}	917^{x}	761^{y}	20
Insoluble but potentially degradable (b)	732^{x}	598^{y}	373^{z}	25
Immediately soluble (a)	196^{x}	319^{y}	389^{y}	25
Rate of digestion (c) (h^{-1})	0.44^{x}	0.85^{y}	0.86^{y}	7.2

x,y,z within rows, values with different superscripts are significantly different ($P<0.05$).

Barley and wheat had a very similar proportion, and oats had a significantly lower proportion of potentially degradable DM. However, the immediately soluble fraction (a) was significantly higher in oats and wheat than barley. The insoluble but potentially degradable fraction (b) was significantly higher in barley than wheat which was significantly higher than oats. Similar data on the DM degradability of barley, wheat and oats have recently been included in the UK tables of nutritive value and feed composition (MAFF, 1990). These are summarised in Table 9.

Table 9. Dry matter degradability of cereals (g kg^{-1} DM incubated or as stated) (after MAFF, 1990).

Degradation characteristics	Cereal		
	Barley	Wheat	Oats
Number of samples studied	16	8	4
Potentially degradable fraction (a+b)	868	941	752
Insoluble but potentially degradable fraction (b)	558	322	172
Immediately soluble fraction (a)	310	619	580
Rate of digestion of 'b' (c) (h^{-1})	0.40	0.38	0.23

These data again indicate that oats has a considerably lower proportion of potentially degradable DM than barley or wheat. They similarly indicate that the immediately soluble fraction (a) is markedly higher in oats and wheat than barley, and that the insoluble but potentially degradable fraction (b) is highest in barley and lowest in oats, although the values quoted by MAFF are considerably different from those of Moran (1986). In addition, the rates of digestion (c) of wheat and oats differ markedly from the values of Moran (1986). It is noteworthy that Kay et al. (1972b) reported that more starch escapes rumen digestion when oats are fed compared with wheat or barley.

In both the studies of Moran (1986) and MAFF (1990), the nylon bag method was used to measure the rumen degradation characteristics. There is some evidence (Michalet-Doreau and Cerneau, 1991), that different pre-treatments of the grain (e.g. fineness of grinding) before incubation can substantially

influence the values obtained for the immediately degradable fraction and the rate of digestion. Because of the importance of defining the degradation characteristics, this area needs urgent clarification.

3.3 Effect of processing

The commonest and probably the most important reason for processing cereal grain is to increase digestibility. There may also be additional benefits, such as improved mixing with other ingredients, and destruction of weed seeds (Tait and Beames, 1988). Processing can affect not only digestibility but also the rate and site of grain digestion and voluntary forage intake. Processing generally increases the rate and extent of microbial degradation of starch in the rumen and decreases amounts of starch digested post-ruminally (Theurer, 1986). Unnecessary processing is wasteful and may be harmful (Campling, 1991) since rapid starch fermentation can depress rumen pH so that cellulolysis is impaired and forage intakes decreased (Ørskov, 1976).

3.3.1 Methods of processing

The main processes have recently been summarised both by Tait and Beames (1988) and by Armstrong and Finlayson (1992). There are essentially two main types of grain processing, physical and chemical. Physical processing can be further sub-divided into cold (mechanical) and heat processing. The main processing techniques are listed under these main types in Table 10.

Table 10. Grain processing techniques.

Physical processing			
Cold (mechanical) processing	Heat processing		Chemical processing
	Dry	Wet	
Cracking	Extruding	Steam rolling	Alkali
Rolling	Micronising	Steam flaking	Acid
Hammer-milling	Popping	Pressure cooking	Formaldehyde
	Roasting	Exploding	
		Pelleting	

3.3.1.1 Physical processing

3.3.1.1.1 Cold (mechanical) processing

The main purpose is simply to break the outer tissues of the grain to allow access of rumen micro-organisms and digestive enzymes with cracking, rolling and milling representing progressively severe treatments. Hutton and Armstrong (1975) provided a detailed review of the effects of physical methods of processing on the nutritive value of cereals for ruminants. There is further detailed discussion in the section (3.3.1.1.3) on nutritional effects of physical processing.

3.3.1.1.2 Heat processing

This causes gelatinisation of starch and increases its susceptibility to microbial break-down in the rumen (Campling, 1991). Armstrong (1972) concluded that in cattle there is little benefit in improving digestibility of barley, wheat or maize with heat compared with cold processing. With sheep, processing, whether hot or cold, generally has little effect on overall digestibility of any of the grains. In reviewing the effects of heat treatment, Papasolomontos and Wilkinson (1976) concluded that heat processing reduces protein degradability in the rumen and increases the efficiency of microbial protein production, resulting in an increased supply of amino acids to the duodenum.

3.3.1.1.3 Nutritional effects of physical processing

There have been a number of comprehensive reviews covering this topic, including Armstrong (1972, 1974), Hutton and Armstrong (1975), Ørskov (1976, 1979), and most recently Tait and Beames (1988) and Campling (1991). Therefore, discussion here is restricted to the most important aspects. Sheep and cattle are considered separately because of the major differences between them.

Sheep: It is well recognised that sheep and goats are far better able to cope with whole grains than cattle (Hale, 1973; Ørskov, 1976). In general, it can be concluded that physical processing of cereal grains is unnecessary, at least for young sheep, and in fact can have undesirable effects (Ørskov, 1979; Barnes and Ørskov, 1982; Tait and Beames, 1988).

Ørskov et al. (1974a) compared barley, oats, maize and wheat, either whole or pelleted, and showed no differences between the two physical forms in terms of rate of gain or feed efficiency in lambs. The review of Tait and Beames (1988) concluded that the digestibility of whole grain by lambs is equal to or superior to that of processed grain. It is also known that pelleted grain can lead to unacceptably soft carcase fat due to the presence of monomethyl-branched chain fatty acids. In high concentrate diets, pelleting can also increase the risk of acidosis and rumenitis (Ørskov, 1980). The feeding of whole compared with processed grain results in a higher rumen pH, so that cellulolysis and forage intakes are optimised (Ørskov and Fraser, 1975). This can be particularly beneficial when substantial amounts of grain are fed as in late pregnancy and lactation (Tait and Beames, 1988), to minimise risks of acidosis and depressed cellulolysis.

However, with mature sheep there is a greater possibility of whole grain passing through the reticulo-omasal orifice, particularly on silage-based diets (Vipond et al., 1985; Chestnutt, 1990 and 1992). Where low to moderate amounts of cereals are fed to ewes in late pregnancy, there can be benefits in complete diet digestibility from the physical processing of cereals (Chestnutt, 1992). Tait and Beames (1988) stated that type of forage and forage:grain ratio may be important factors affecting the potential benefit from physical processing of cereals for ewes. There is also known to be wide variation in grain utilisation between individual ewes (Vipond et al., 1985).

Cattle: In contrast to sheep, there are usually very marked improvements in digestibility from the physical processing of grains for cattle (Nordin and Campling, 1976). In general, it can be concluded that processing of barley and wheat is necessary, at least for large cattle. A useful comparison of the generalised effects of mechanical processing of grains for sheep or cattle was recently provided by Armstrong and Finlayson (1992), and this is repeated in Table 11.

The marked differences between sheep and cattle mainly relate to the differences in physical size of the reticulo-omasal orifice. With smaller ruminants, the grains do not readily pass the orifice, so are usually cracked during rumination if they have not been previously. This factor also affects utilisation of grains by smaller cattle. In fact, Ørskov (1987) concluded that physical processing was unnecessary for cattle less than 150 kg live

weight. However, Campling (1991) concluded that processing would result in considerable production benefits in young cattle fed mixed (forage/concentrate) diets. Although there may be few, if any, benefits from processing of grain for young cattle fed high grain diets (Campling, 1991), a sensible general recommendation would probably be to carry out minimal physical processing of barley or wheat for all ages of cattle. This recommendation also applies to lactating cows, though there have been relatively few studies on the effects of cereal processing for dairy cows (Tait and Beames, 1988).

Table 11. Apparent digestibility of organic matter (OM) of whole, rolled or ground and pelleted cereals when fed to sheep or cattle.

Cereal	Apparent digestibility of OM			
	Sheep		Cattle	
	Whole	Ground and pelleted	Whole grain	Rolled grain
Wheat	0.83[1]	0.87[1]	0.53[2]	0.88[5]
Barley	0.81[1]	0.77[1]	0.50[2]	0.78[5]
Maize	0.84[1]	0.82[1]	0.62[3]	0.80[3]
Oats	0.70[1]	0.68[1]	0.59[4]	0.83[5]

1, data of Ørskov et al. (1974a) and Ørskov et al. (1974b).
2, data of Bergner and Weissbach (1983).
3, data of Wilson, Adeeb and Campling (1973).
4, data of Morgan and Campling (1978).
5, data of Nordin and Campling (1976).

However, oats may be an exception to this general rule. A number of authors have concluded that there is little benefit to be gained from processing oats for young cattle (Morrison, 1950; Morgan and Campling, 1978; McDonald and Hamilton, 1980). Indeed, Campling (1991) in a review of processing cereal grains for cattle, concluded that whole oats can be used efficiently by both lactating cows and beef cattle. It has been suggested that the fibrous husks of oats may stimulate rumination to a greater extent than other cereals, and

that the lower density of oats may increase the length of time the grain remains in the rumen (Nordin and Campling, 1976).

3.3.1.1.4 **Extent of processing**

Minimal physical processing of grain is regarded as adequate, and in fact desirable, for cattle (Ørskov, 1987). Excessive processing is generally regarded as wasteful and potentially harmful through the increased rate of break-down of the grain, and the decreased rumen pH which results (Ørskov 1976, 1979, 1986). Nordin and Campling (1976) reported that rolling is as effective as grinding to increase digestibility of grain for cattle, and rolling may minimise the risk of digestive upset (Tait and Beames, 1988).

3.3.1.2 **Chemical Processing**

Effects vary depending on the particular chemical used.

3.3.1.2.1 **Acids**

Organic acids are primarily used as preservatives to control fungal organisms (Tait and Beames, 1988) and propionic acid is commonly used to good effect on commercial farms in the United Kingdom for this purpose. There appears to be little effect of organic acids on the physical and chemical properties of cereal grains, except for a reduction in the level of alpha-tocopherol (vitamin E) (Lawrence, 1982). If left uncorrected this can lead to deficiency diseases such as muscular dystrophy.

3.3.1.2.2 **Alkali**

Sodium hydroxide, calcium hydroxide and ammonia have all been used for treatment of cereal grain for ruminants. Most research effort has concentrated on sodium hydroxide treatment, and there is now considerable commercial interest in this. There appears to be little information available on other alkali treatments. Calcium hydroxide is reported to be a less effective preservative than sodium hydroxide (Berger et al., 1981). Ammonia treatment of grain has been shown to increase digestibility in adult wethers (Brand et al., 1985) but the efficacy of treatment has not been fully evaluated (Campling, 1991).

3.3.1.2.2.1 **Sodium hydroxide**

This method, originally described by Ørskov and Greenhalgh (1977) has the potential to increase organic matter digestibility to that achieved by physical processing. It also results in an alkaline product, and one which is aerobically stable even when moist.

Unsuccessful attempts were made to develop the method onto a commercial scale in the early 1980s. The main reason for failure on a farm scale at this time was the large amount of cereals treated at one time (approximately 12 t/hour) and not subsequently moved to allow dissipation of heat resulting from the chemical reaction. As a result, the grain seriously moulded and formed solid blocks. There were also problems of excessive urination in beef cattle fed large amounts of treated grain, which had unacceptable animal welfare implications. More recently, there has been a revival of interest in sodium hydroxide treatment of cereal grain (mainly wheat), especially on silage-based diets. There has been considerably more success on commercial farms because only relatively small amounts are now treated at any one time in mixer wagons, and the grain is turned shortly after treatment to allow heat to dissipate. As a result, the earlier problems of moulding and of grains adhering together in a large solid mass are avoided.

3.3.1.2.2.1.1 **Application rate of sodium hydroxide**

The effects of different sodium hydroxide contents on cereal grain digestibilities were compared with rolled grain when fed as the sole dietary ingredient to one-year old friesian steers (Ørskov et al., 1980). This showed that the amounts of sodium hydroxide required to increase organic matter digestibility to that obtained by rolling, depending on grain type. More sodium hydroxide was needed with the more fibrous barley and oats (30-35 g kg^{-1}) than with wheat or maize (15-30 g kg^{-1}). Subsequent studies with sodium hydroxide treated grain fed in mixed diets with hay, showed that larger amounts of sodium hydroxide were necessary than in diets where sodium hydroxide treated grain was given as the sole feed (Ørskov et al., 1980). Rates of 30 and 50 g sodium hydroxide kg^{-1} for wheat and barley respectively are currently recommended for successful treatment of grain in commercial practice, but the moisture content of the grain is also an important consideration (A. Reeve, Pers. Comm.).

3.3.1.2.2.1.2 Sodium hydroxide - potential problems

Largely depending on sodium hydroxide application rate, sodium content of treated grain may be 100-200 times higher than the levels of 0.1-0.3 g kg^{-1} DM typical of untreated grain (MAFF, 1990). It is therefore extremely important that livestock fed sodium hydroxide treated grain should have unrestricted access to clean water. Although ruminant livestock are very tolerant of high sodium intakes provided that clean drinking water is freely available, high intakes of sodium hydroxide treated grain can lead to excessive urination, which is undesirable. Probably related to this, sodium hydroxide treated grain fed in large amounts to cattle has also resulted in kidney damage (Nelson, 1980). In commercial practice, the feeding of sodium hydroxide treated grain is usually limited to about 25% of total diet dry matter, or to 4-5 kg dry matter per day for lactating dairy cows.

Sodium hydroxide treatment also destroys any fat soluble vitamins present in the grain, so supplementation needs to take account of this, especially in diets where a high proportion of treated grain is included. There is a particularly high risk of vitamin E deficiency when large amounts of treated grain are fed and other feedstuffs are low in vitamin E (Rice and Kennedy, 1988).

3.3.1.2.3 Formaldehyde

There have been a number of studies over recent years which have examined the effects of formaldehyde treatment on the nutritive value of different types of cereal grains (Kassem et al., 1987; Peiris et al., 1988; Hyslop et al., 1989; Fluharty and Loerch, 1989; Morgan et al., 1989; Oke and Loerch, 1989). In contrast to physical processing, the aim of formaldehyde treatment is not to increase digestibility but to reduce rumen degradability of starch and nitrogen. The reduced degradabilities of starch and protein should result in increased supplies of glucose and amino acids to the small intestine, which might have beneficial effects on animal performance. Owens et al. (1986) concluded that, in growing cattle, starch was used 42% more efficiently when digested in the small intestine.

The effects of formaldehyde treatment of grain vary, for reasons which are not fully understood. With maize, formaldehyde treatment has significantly reduced the digestion of starch in the rumen and significantly increased it

in the small intestines of both steers (John, 1976) and sheep (Oke and Loerch, 1989). Hyslop et al. (1989) also found that formaldehyde treatment of barley or wheat reduced in sacco degradability of protein-free dry matter in sheep. However, in vivo studies have not shown an increased supply of starch to the small intestine when formaldehyde treated barley was fed to sheep (Morgan et al., 1989; Ortega-Cerrilla and Finlayson, 1991). Kassem et al. (1987) showed variable results in milk production to formaldehyde treatment of barley. In the two out of three experiments which used a higher rate of formaldehyde application, significant increases in silage intake and milk production were observed.

There is evidence that the effect of formaldehyde treatment is less in whole compared with milled or rolled grain (Hyslop et al., 1989). Since whole grain can usually be successfully fed to sheep, but not to most classes of cattle, it could be argued that the main benefits of formaldehyde treatment are likely to be in cattle diets. Although formaldehyde treatment has sometimes resulted in significant nutritional effects, the future of the treatment may be questioned in view of possible future bans on the use of formaldehyde in animal feeds.

3.4 Effect of dietary inclusion

The balance in the diet of carbohydrates which are fermented quickly (e.g. from cereals) and slowly (e.g. from forage) has a fundamental influence on rumen pH, and hence also on rumen VFA proportions (Sutton, 1976). When hay is the only feed, about three times more acetic acid is produced than propionic acid. Increasing the ratio of cereal to forage decreases the ratio of acetic to propionic acids, and reduces energy loss as methane (Webster, 1987). A specific example of the effect of cereal inclusion rate on rumen VFAs is given in Table 12, based on the studies of Sutton et al. (1980). As the proportion of barley-based concentrate:hay increased from 60 to 90% of the diet, the rates of production and proportions of acetic and butyric acids decreased, and propionic acid increased. In addition, the duodenal flow of starch increased from 0.45 to 0.55 kg d^{-1} at the higher cereal inclusion.

The broad relationship between rumen pH and rumen VFAs on diets of long forage and cereal-based concentrates has been described by Sutton (1981). Generally, a reduction in rumen pH leads to a decreased ratio of acetic acid: propionic acid. Decreases in the ratio of acetic plus butyric:propionic

acids have also been related to decreases in milk fat content (Sutton, 1981; Sutton et al., 1988). This is thought to be related to the role of propionic acid as a stimulus for insulin release (Sutton et al., 1986), which may lead to an increase in fat synthesis in fatty tissue, leading in turn to a reduction in milk fat synthesis by the mammary gland (Finlayson, 1989). Ratios of 3 or less for acetic:propionic acid (Armstrong and Prescott, 1971) and of 4 or less for acetic plus butyric:propionic acid (Sutton, 1981) have been associated with low milk fat contents.

Table 12. Rumen VFA production in lactating cows fed different dietary hay: concentrate ratios (after Sutton et al., 1980).

	Barley-based concentrate (%)	
	60	90
Rumen VFA (molar %):		
Acetic	61	43
Propionic	22	41
Butyric	12	9
Rumen VFA production (mol d^{-1}):		
Acetic	45	31
Propionic	16	29
Butyric	9	6

Research effort has, until recent years, concentrated on the effects of high rates of cereals in ruminant diets (i.e. potentially low rumen pH, low acetic plus butyric:propionic acid ratios, acidosis, low milk fat syndrome). More recently, there has been a change of emphasis to examine the effects of lower level supplementation with carbohydrate and protein sources, especially to silage-based diets (see reviews by Thomas and Gill, 1988; Thomas and Rae, 1988; Thomas and Thomas, 1989). Although the efficiency of microbial protein synthesis can be increased by supplementing silage with protein (Rooke et al., 1983, 1985), an alternative approach is to provide a readily fermentable carbohydrate source to increase capture of silage nitrogen. Such supplementation of grass silage with barley has resulted in modest improvements in microbial efficiency (Thomas et al., 1980; Rooke et al.,

1985). There is further discussion related to silage as a basal feed in Section 3.6.

Most studies have shown that the ratio of acetic plus butyric: propionic acids decreases as the amounts of concentrate in diets increase. However, recent work (Poots and Unsworth, 1990) using a grass silage based diet, with relatively low rates of high protein concentrates (340 g kg^{-1}) for dairy cows, has indicated that the proportions of both propionic and butyric acids were increased with increasing rates of supplementation from 2.5 to 4.5 kg $head^{-1}$ per day. This may be significant, particularly in relation to the increased butterfat content of the milk (44.2 g kg^{-1} versus 48.1 g kg^{-1}) and increased milk yields (12.7 versus 15.1 kg^{-1} day).

3.5 **Frequency of feeding**

In rations containing very high proportions (70-90% of total diet dry matter) of cereal-based concentrates, there is clear evidence that increased frequency of feeding (6 compared with 2 x daily) can be an effective way of avoiding low rumen pH and low milk fat production. (Sutton et al., 1985). However, this same experiment showed that, when concentrates comprised 60% of total dry matter, there was little difference in milk fat content and fat production between 2 and 6 meals per day. The main results are summarised in Table 13. Mould (1988) has described the generalised changes in rumen pH in response to method of feeding. Owen (1978) also reported that increased frequency of feeding improved dry matter and nitrogen digestibility, and decreased diurnal variation in the rumen concentrations of both VFAs and ammonia.

An alternative but equally effective approach is complete diet feeding (Rickaby, 1978, 1979). This results in a fixed ratio of forage and concentrates always fed together, which minimises the likelihood of major fluctuations in rumen pH. It should perhaps be added that although complete diet feeding can be very effective and economic, there are many situations where it may not be suitable and other feeding methods can and do work very effectively.

Table 13. **Effect on milk production of feeding barley-based concentrates 2 or 6 times daily in a fixed ration of hay and concentrates providing about 180 MJ digestible energy daily (after Sutton et al., 1985).**

Concentrates (% of diet):	60		70		80		90	
Feeds per day:	2	6	2	6	2	6	2	6
Milk yield (kg d^{-1})	19.4	20.8	19.7	20.2	20.6	24.5	23.0	21.4
Fat yield (kg d^{-1})	0.70	0.75	0.65	0.79	0.65	0.83	0.42	0.62
Fat content (g kg^{-1})	35.9	36.0	32.6	39.2	31.6	33.8	17.9	29.7

3.6 Effect of basal diet

It has already been noted that many experiments have been undertaken to investigate the effects of high levels of cereals in diets, often with hay fed as the basal forage. Thomas and Rae (1988), in a review of the effects of concentrate supplementation of silage for milk production, reported that most experiments show milk fat depression and elevation of milk protein content from increasing concentrate input. It has been suggested that high propionate fermentations are not so apparent in silage based, as in hay based diets containing a high proportion of concentrates (Thomas and Chamberlain 1982), but this is not supported by Rohr (1980).

3.6.1 Silage based diets

Since grass silage is now by far the most important conserved forage fed in the UK, some consideration of its important attributes is necessary.

There is evidence that the efficiency of utilisation of metabolisable energy (ME) for maintenance and fattening is less for silage than that predicted for other non-fermented forages (Thomas and Thomas, 1985). There is also evidence that the efficiency of utilisation of ME for lactation (kl) is reduced when silages make up a high proportion of the diet. When silages were fed as the sole feed, Rae et al. (1987) reported kl values which ranged from 0.54-0.58 in comparison with predictions of 0.61-0.63. These values are consistent with the kl values determined in calorimetric studies, which were 16% lower than predicted (Unsworth and Gordon, 1985). It has been suggested

that the low kl values for silage diets are related to an imbalance in energy and protein supply, and supplementation with carbohydrate or protein sources has been shown to increase microbial efficiency (Thomas and Rae, 1988).

There is now considerable evidence that diets containing a high proportion of silage support low yields of microbial protein. The Agricultural Research Council (ARC) (1984) suggested a mean microbial nitrogen yield of 32 g kg^{-1} organic matter apparently digested in the rumen (DOMR) in sheep and cattle offered a range of diets, whereas grass silage appeared to support a mean of only 23 g kg^{-1} DOMR. The main reason for this low efficiency is thought to be the poor ATP (energy) yield from silage fermentation products compared with sugar (Thomas, 1982), since on silage diets approximately 85% of ME available to the animal is in the form of VFAs absorbed from the rumen (Gill et al., 1986). In addition, the generally high solubility of silage nitrogen and the consequent high concentration of rumen ammonia is also thought to be one of the main factors associated with the low microbial efficiencies typical of silage diets (Thomas and Gill, 1988). As a result of this deficiency in energy supply, and the rapidity of release of ammonia from silage nitrogen compounds, it can sensibly be argued that supplementation with readily fermented carbohydrate sources would improve microbial fixation of ammonia.

Starch supplements such as barley can reduce ammonia concentration, increase microbial protein synthesis (McMeniman and Armstrong, 1977) and enhance nitrogen retention in sheep and cattle (Thomas and Thomas, 1985). However, there is evidence that rumen microbes utilise nitrogen more effectively when silage is supplemented with sugar rather than starch (Syrjala, 1972). Rooke et al. (1987) reported that silage supplemented with glucose resulted in reduced rumen ammonia nitrogen concentrations, as well as increased flow of non-ammonia nitrogen to the duodenum, and an increased efficiency of microbial protein synthesis. A supplement of casein and glucose caused further increases in non-ammonia nitrogen flow and microbial efficiency suggesting a possible synergistic effect of protein and sugar.

The apparent difference between sugar and starch may relate to the rate of fermentation of the carbohydrate source, but this is not fully understood. Indeed, Thomas and Rae (1988) stated that the response in microbial efficiency to carbohydrate or protein supplementation of silage is sporadic

and unpredictable. This is clearly an area for further research, bearing in mind the importance of silage in UK diets.

4.0 METABOLISABLE ENERGY CONTENTS

4.1 Values measured *in vivo*

Despite the importance of cereal grains in ruminant diets, there have been relatively few measurements of ME content made *in vivo* for cereals grown in the UK. Table 14 summarises for barley, wheat and oats the sets of data *in vivo* produced by the Rowett Research Institute (RRI) (1976), Wainman *et al.* (1979) and the ADAS Feed Evaluation Unit (1988, 1989a,b). The values obtained are contrasted with the historical values quoted by MAFF *et al.* (1975), the origin of which is uncertain but which were extensively used for diet formulation purposes until recently. Recent values obtained for naked oats (Givens and Brunnen, 1987) are also included in Table 14 for completeness. It is notable that the values for wheat and barley reported by RRI (1976) and Wainman *et al.* (1979) were generally lower than the historic data of MAFF *et al.* (1975). However, the more recent values produced by the ADAS Feed Evaluation Unit (1988, 1989a,b) are more in line with the historic values of MAFF *et al.* (1975).

Wainman *et al.* (1984) reported on the ME contents of three samples of barley grain of low specific weight. These had specific weights and 1000 grain weights covering the ranges 49.9-62.1 $kghl^{-1}$ and 18.1-34.1g respectively. The results indicated that whilst there was no significant difference in the ME contents of the three samples, the authors concluded that there was a tendency towards a lower ME content in the samples with the lowest specific weights. Wainman *et al.* (1984) also reported on a reanalysis of the data of RRI (1976). This showed no significant relationship between either specific weight or 1000 grain weight and ME content.

There remains some uncertainty about the ME content of cereals, although since ME content is likely to be related to digestibility, the factors which influence this aspect are likely to influence ME content also. Further clarification of the effect of grain size and specific weight is also required. There is little information on the influence of variety on ME content for ruminants although McNab (1991) has shown some effect of variety on the ME content of wheat for poultry.

Table 14. Metabolisable energy values of cereal grains measured *in vivo*.

Cereal	Metabolisable energy ($MJ^{-1}kg$ DM)			Reference
	Mean	SD	Range	
Barley	13.7	-	-	MAFF *et al*. (1975)
	12.9	0.70	11.7-14.6	RRI (1976)
	13.5[1]	0.39	12.9-13.9	ADAS FEU (1989a)
Wheat	14.0	-	-	MAFF *et al*. (1975)
	13.5	-	11.7-14.8	Wainman *et al*. (1979)
	13.8[1]	0.28	13.4-14.1	ADAS FEU (1989b)
Oats	11.5	-	-	MAFF *et al*. (1975)
	12.0	1.1	9.6-13.6	RRI (1976)
	12.4[1]	0.90	11.1-13.4	ADAS FEU (1988)
Naked oats	14.7	0.46	14.2-15.3	Givens and Brunnen (1987)

1, Values for rolled cereals quoted.

4.2 Prediction of energy value from laboratory measurements

With the exception of the report of Pickering *et al*. (1982), there appears to be no report which has specifically related energy value to laboratory measurements. These authors suggested that the energy value of oats may be predicted from grain volume to weight ratio or acid detergent fibre content.

For any laboratory method successfully to predict the ME content *in vivo*, a large set of cereals with measurements *in vivo* is required. Such a large calibration set is not available for UK produced cereals.

5.0 PROTEIN CONTENT AND QUALITY OF CEREAL GRAINS

5.1 Introduction

The crude protein content of cereal grains varies considerably, according to cereal type, variety, soil fertility, fertiliser application and climate. The majority of the grain protein is concentrated in the endosperm with the remainder in the bran and germ. The concentration of protein increases from the centre of the endosperm to the periphery. The most important proteins present in the endosperm are prolamin (gliadin) and glutelin (glutenin), which collectively are referred to as 'gluten'. These proteins are regarded as storage proteins. The principal amino acids present in wheat gluten are glutamic acid and proline. Gluten has elastic properties which are important

for bread making, but may limit the use of cereals in ruminant diets. The crude protein content and the nitrogen degradability characteristics of wheat, barley and oats have been reported by MAFF (1990) and are summarised in Table 15. The immediately soluble nitrogen and effective degradability values for wheat are considerably higher than the values of 26.2 and 76% respectively reported by Fahmy et al. (1991).

Table 15. Crude protein contents and nitrogen degradability characteristics of cereal grains (after MAFF, 1990).

	Barley	Wheat	Oats
Crude protein (g kg^{-1} DM)	129	126	105
(range)	(103-160)	(97-157)	(79-132)
Nitrogen degradability			
a (%)	24.5	45.0	72.0
b (%)	69.7	51.0	23.4
c (h^{-1})	0.35	0.38	0.40
Effective degradability (%) @ outflow rate:			
$0.02h^{-1}$	90.3	93.3	94.5
$0.05h^{-1}$	85.2	89.7	92.8
$0.08h^{-1}$	80.9	86.6	91.5

a, immediately soluble fraction.
b, insoluble but degradable fraction.
c, rate of degradation of 'b' fraction.

Dietary proteins, peptides and amino acids are subjected to microbial degradation in the rumen. Nitrogen from this degradation process may be used for microbial protein synthesis. The deaminated protein carbon skeletons are converted to volatile fatty acids, and the energy released is used for microbial growth. Therefore, nitrogen degradability characteristics of cereals are a more important measure of protein quality in ruminant nutrition than amino acid composition per se.

Grain protein content is thought to be a key factor in determining the rate of starch digestion, as the starch granules in the grain are surrounded by a protein matrix (Mathison et al., 1991).

5.2 Effect of cereal species and variety

The influence of species and variety on protein content and quality of cereal grains is confounded by the effects of soil type, fertility and climate and therefore, few comparable data are available. However, there is a strong negative correlation between grain protein concentration and yield of DM (Pushman and Bingham, 1976; Blackman, 1980; Riggs, 1984). While the quantity and quality of protein are of importance for bread making and malting, quality described in terms of amino acid composition and the physical characteristics this imparts is less important for ruminants.

Six rowed barley varieties have a greater proportion of fibrous husk than two rowed varieties, leading to a dilution of the other cereal grain constituents. This can result in a 10-20 g kg^{-1} variation in grain protein content. Welch and Gosden (1983) examined the variation in grain protein content and grain protein yield in 17 barley varieties. They found a two-fold variation in grain protein content (76-160 g kg^{-1} DM) and a three-fold variation in grain yield (2.39-7.31 t ha^{-1}), producing a four-fold range in grain protein yield (255-959 kg ha^{-1}). However, the mean grain protein contents and protein yield were not significantly different between the winter and spring crops. The mean varietal variations in grain protein content were reported by Welch and Gosden (1983) as being 12 g kg^{-1} for spring varieties and 16 g kg^{-1} for winter varieties. Dent et al. (1968) found a varietal range of 8-15 g kg^{-1} in grain protein content.

Some limited nitrogen degradability data are available for the different cereal species (MAFF, 1990; Fahmy et al., 1991). However, no nitrogen degradability data appear to have been published for individual varieties. The composition of the protein matrix in the starchy endosperm of the grain is known to vary according to variety (Shewry et al., 1979). The significance of any differences in nitrogen degradability of different cereal species and varieties in terms of ruminant nutrition have yet to be quantified. Furthermore it is known (Michalet-Doreau and Cerneau, 1991) that different procedures used to measure nitrogen degradability of cereals can influence the values obtained. More information on this area is required.

5.3 Effect of fertiliser nitrogen

The majority of papers in this area have focused on the relationship between

fertiliser application, and other agronomic factors, and crop yields. However, Needham (1984) reported that grain nitrogen content is increased by increasing application of nitrogen. The response in grain nitrogen content to nitrogen fertiliser appeared linear when the fertiliser was applied following early stem extension, irrespective of any yield response. Due to the influence of other factors such as site and climate, it is difficult to predict the response in grain nitrogen content to nitrogen application. This was demonstrated by Powlson et al. (1984) who studied the recovery of ^{15}N-labelled fertiliser by winter wheat. Recovery of labelled nitrogen applied to the crop ranged from 55-69% in 1980-81, and nitrogen recovery in the grain ranged from 37-44%. These differences in nitrogen recovery in the crop were attributed to the differences in the soil conditions between application and uptake. Recently, Dampney (1992) reported on a series of experiments examining the effect of rate and timing of nitrogen fertiliser applied to milling wheat. He concluded that extra nitrogen would increase grain protein content by 4-7 g kg^{-1} DM per 30 kg ha^{-1} of nitrogen applied. In addition, Dampney (1992) reported that foliar urea applied to the wheat during the milky ripe development stage would give a larger increase in grain protein content (approximately 5-7 g kg^{-1} DM per 30kgN ha^{-1}) than ammonium nitrate applied at the second node stage (4-5 g kg^{-1} DM per 30kgN ha^{-1}). In addition, McNab (1991) showed that the concentrations of essential amino acids in wheat were increased by levels of fertiliser nitrogen up to 350kg ha^{-1}.

Environmental factors also appear to be important in the production of high protein bread making wheats. Riggs (1984) reported that the protein contents of bread making wheats produced in Canada, USA, Eastern Europe and the Mediterranean area were high due to high temperatures and moisture stress after heading. These two factors restrict the period of grain filling, which reduces yields, but increases grain protein content. Whilst fertiliser nitrogen can clearly influence grain protein content, there appear to be few data relating protein content to its nutritional quality for ruminants.

5.4 Effect of processing

In addition to influencing the sites of starch digestion in the digestive tract, cereal processing can also influence the availability of cereal protein to the rumen micro-organisms. Armstrong (1972) compared the degradability of micronised barley samples with an untreated control.

Protein solubility in rumen liquor was used as a measure of rumen protein degradability. Increasing the length of heat treatment and the temperature decreased protein solubility in the rumen, and at the same time increased starch availability from 0.32 to 0.98. The effects of formaldehyde treatment on nitrogen degradability are referred to earlier in Section 3.3.1.2.3.

6.0 CEREALS IN DIETS

6.1 Milk production

6.1.1 Effect of cereal species

The relative nutritive value of a cereal grain will depend on its proportion in the diet, its degree of processing, other dietary constituents and also the level of milk production (Moran, 1986). Method of feeding might also exert an effect.

On the basis of metabolisable energy content, oats are inferior to barley which is on average inferior to wheat. However, milk production responses are variable. Both Tommervik and Waldern (1969) and Jeffery et al. (1976) reported similar yields of fat-corrected milk with oats, barley and wheat, whereas Gomez (1975) and Moss and Prier (1981) noted higher fat corrected milk yields from cows given oats. Moran (1986) compared the nutritive value of rolled wheat, barley and oats when each was given as a major component (60% of total dry matter intake) with oat silage and lucerne hay in a complete diet fed to high yielding dairy cows. A summary of the results is given in Table 16.

Total DM intakes were not significantly different, but the oats diet resulted in the highest milk yield. Oats also resulted in a significantly higher butterfat production than either barley or wheat, but milk protein content was significantly lower than from either barley or wheat. The only significant difference between barley and wheat was that wheat resulted in the highest milk protein yield.

Heikkilä et al. (1988) carried out five experiments comparing coarsely ground barley and oats as the sole concentrates with grass silage-based diets for Ayrshire cows in early lactation. There was no significant difference in total DM intake between barley and oats. Milk yields were slightly higher on

oats compared with barley (21.3 versus 20.2 kgd^{-1}) but butterfat and milk protein contents were consistently lower on the oats diets. Martin and

Table 16. Different cereals for milk production (after Moran, 1986).

	Barley	Wheat	Oats	Significance
Dry matter intake ($kg\ d^{-1}$)	16.9	18.1	17.7	NS
Milk yield ($kg\ d^{-1}$)	22.9	24.0	25.1	NS
Butter fat ($g\ kg^{-1}$)	45.5	41.9	47.2	
($kg\ d^{-1}$)	1.04^{b}	1.01^{b}	1.19^{a}	P<0.05
Milk protein ($g\ kg^{-1}$)	35.2^{a}	38.4^{a}	31.2^{b}	P<0.05
($kg\ d^{-1}$)	0.81	0.92	0.78	

a,b. Different superscripts indicate significant (P<0.05) differences.

Thomas (1988) found that milk yields were significantly higher (P<0.05) with oats (17.1 kgd^{-1}) than with barley (15.9 kgd^{-1}), fed together with hay and soyabean meal. There were no significant differences in fat or protein yields in this experiment.

Finlayson (1989) when discussing the results of Moran (1986) has suggested that the increased milk fat and reduced protein concentrations with oats compared with barley or wheat, may relate to higher ratios of acetic plus butyric:propionic acids in the rumen. However, the results of Heikkila *et al*. (1988) and Martin and Thomas (1988) question whether this necessarily occurs.

Rations containing different ratios of triticale and barley have been compared using *ad lib* alfalfa silage as the basal forage for Holstein dairy cows (McQueen and Fillmore, 1991). There were no significant effects on dry matter intakes, milk fat or protein content, or fat corrected milk yields, though the milk yields were 23.6, 26.6 and 24.7 kgd^{-1} for the three dietary treatments of 100% barley, 57% barley + 43% triticale and 14% barley + 86% triticale respectively.

There appear to have been relatively few studies with wheat. Indeed, Laurent (1988) in a review of the utilisation of wheat and other cereals concluded

that wheat is little used in dairy cow diets. However, it is now used quite commonly as a straight feed for cows in the UK. It is estimated that 0.63 million t of wheat (compared with 1.83 million t of barley) were directly fed on farms in England and Wales in 1990/91 (HGCA, 1992). The results of Moran (1986) showed little difference in milk production from feeding barley or wheat in a complete diet, but method of feeding and basal diet would be expected to exert significant effects.

Milk production responses are poorer with oats than with maize (Fisher and Logan, 1969), and at normal rates of feeding are probably poorer with barley, though cereal inclusion rate is known to influence this (Sutton et al., 1980). As discussed earlier in Section 3.2, maize is generally less fermented in the rumen than barley or wheat, so that 20-40% of starch may escape rumen fermentation (Sutton, 1981). In consequence, maize tends to support a higher ratio of acetic plus butyric:propionic acids in the rumen and hence a higher milk fat content (Balch, 1972; Sutton et al., 1980).

6.1.1.1 Composition of milk fat

Differences in milk fat composition have been observed when oats replaced barley or wheat in the diet of dairy cows (Kankare and Antila, 1984; Moran, 1986; Martin and Thomas, 1988; Heikkalä et al., 1988). In general, oats significantly reduced the concentration of saturated fats in milk, which resulted in an increase in unsaturated acids, mostly mono-unsaturates. The mechanism for these changes, according to Martin and Thomas (1988), would appear to be a reduction of mammary sythensis of C6-C16 fatty acids, due to the higher lipid content of oats affecting rumen fermentation. Additional unsaturated fatty acids from the diet are hydrogenated in the rumen and the C18:0 fatty acids subsequently desaturated in the mammary gland.

There have been a considerable number of studies comparing milk production in cows fed either barley or oats, with recent interest focussing on the manipulation of milk fat composition. This has been stimulated by the suggested links between the consumption of saturated fatty acids and the development of coronary heart disease in man. Milk products from oat fed cows might assist in a reduced consumption of saturated fatty acids (Martin and Thomas, 1988). Worthy though these studies are, oats are currently little used in practical UK diets.

6.1.2 Effect of cereal processing

6.1.2.1 Physical processing

Minimal physical processing of cereals, certainly of barley or wheat, is very probably advisable, though there have been relatively few studies on the effects of processing for dairy cows (Tait and Beames, 1988). As previously discussed in section 3, excessive processing is likely to result in depression of rumen pH and associated digestive problems. Campling (1991) in a review of cereal grain processing for cattle, found only one report (Valentine and Wickes, 1980) which compared whole and processed barley for lactating cows. Milk production was lower on whole barley compared with rolled or sodium hydroxide treated barley, when the cereals formed either 25% or 50% of ME requirement.

Oat grain appears to be the exception to the rule that grain should be processed for lactating cattle (Campling, 1991). Two experiments by Hodge et al. (1984) and Valentine and Bartsch (1989) have compared whole with crushed oats as supplements for grazing lactating cows and in both there was no significant difference in milk production though 24% of the whole oat grain was excreted in the latter study. When feeding complete diets, Moran (1986) reported similar milk yields from cows fed whole or rolled oats, though whole oats resulted in a lower milk protein content.

6.1.2.2 Chemical processing

6.1.2.2.1 Sodium hydroxide

As previously discussed, there is currently considerable interest in this method of grain treatment amongst UK dairy farmers. It has been reported that sodium hydroxide treated grain is fermented more slowly than physically processed grain, which can lead to increases in forage intake (Ørskov et al., 1980). It is also commonly suggested that the high pH and sodium carbonate content of treated grain may exert important buffering effects, particularly on silage-based diets, but hard evidence of this is limited. Such an effect has been shown in complete diets of hay and concentrates (Ørskov and Reid, 1979), but the forage:concentrate ratios were low (30:70 and 20:80 in the dry matter). Cows fed sodium hydroxide treated barley compared with rolled barley had a significantly higher ratio of acetic plus butyric:propionic

acids in the rumen, which probably resulted in their marked increase in butterfat content and slightly increased butterfat production. However, actual milk yield was lower on the sodium hydroxide treated barley compared with the rolled barley-based diet.

A recent trial by O'Mara et al. (1992) compared milk production from cows fed complete diets based on grass silage and different types of concentrates. This included a comparison of ground and sodium hydroxide treated wheat, which formed 50% of the concentrate dry matter, and 20% of the total diet dry matter intake. There were no significant differences in milk yield, milk protein content or butterfat content (and hence protein or fat production) between the two treatments. It might be argued that feeding as a complete diet, with wheat fed at quite low rates, may have minimised effects on intake and milk production. Bettanay (1980) using complete diets for cows, showed that rolled and alkali treated barley were of similar value for milk production. Moran (1986), again feeding complete diets, reported similar milk yields but significantly higher butterfat content from cows fed alkali-treated oats compared with rolled oats. Campling (1991) concluded that, although sodium hydroxide treatment of barley has been shown to be effective in ensuring complete digestion of starch, similar results for wheat were not available for lactating cows. The subsequent work from O'Mara et al. (1992) has provided some useful data, but there is some need for further information on the effects of sodium hydroxide treated grain (especially wheat) on voluntary forage intakes and milk production.

6.1.2.2.2 Formaldehyde

The principles and main effects of this treatment were described in Section 3.0. Studies with the dairy cow (Kassem et al., 1987) have shown that significant increases in silage intake and milk yields can result from treatment, provided an adequate rate of formaldehyde is applied.

6.1.3 Effects of inclusion rate of cereal in the total diet and amount of cereal fed

Commercially, the amount and type of concentrates (including cereals) fed mainly depends on the target milk production and the amount and quality of forage available, as well as on the relative prices of alternative feedingstuffs.

There has been a considerable research effort on the response in milk solids output to starch-based concentrates. In a review of the literature, Thomas (1980) derived an average value of +0.79kg of solids corrected milk per kg of additional concentrate. Beever et al. (1991) stated that increasing energy intake through the strategic use of concentrates would give consistent increases in milk output, generally accompanied by substantial increases in milk protein content and hence increased protein yield. However, there is known to be a wide variation in response to concentrates (Thomas, 1980), which is not surprising in view of the many variables, both dietary and animal.

In general, as amounts of concentrates fed increase, so forage intake decreases. The decrease in intake of forage DM per kg increase in concentrate DM is called the substitution rate.

Thomas (1987) in reviewing the literature concluded that substitution rate in dairy cows fed silage-based diets averaged 0.52, but emphasised a wide range in values of 0.06-1.29. It is known that highly digestible forages often lead to high substitution rates (Moisey and Leaver, 1984), but other factors such as fermentation also exert an effect. It is more correct to say that forages of high intake potential generally give rise to high substitution (Thomas 1987). It has also been suggested that substitution rate depends on concentrate type, and this is discussed in Section 6.1.4.3.

As previously discussed in Section 3.0, diets containing high proportions of cereals tend to depress rumen pH, and hence the ratio of acetic plus butyric:propionic acids in the rumen. Cellulolysis is impaired and milk fat production decreases. The studies of both Broster et al. (1979) and Sutton et al. (1980) demonstrate the effects of altering the ratio of hay:barley-based concentrates at fixed digestible energy intakes, throughout a large part of lactation. When the hay:concentrate ratio was reduced from 40:60 to 10:90, milk yields and protein yields increased, but fat content decreased, in both experiments (see Table 17).

One might generally conclude that, as the proportion of barley-based concentrates increases above 60-75% of total diet dry matter, fat content and fat production decrease but milk yield and milk protein yield increase. There is a lack of evidence with wheat-based concentrates, but it seems likely that similar effects could be expected. However, it is known that

milk production responses differ when ground maize is used in place of rolled barley (Flatt et al., 1969; Sutton et al., 1980). In both these experiments, reducing the ratio of hay:concentrates from 60:40 to 20:80 (Flatt et al., 1969) or 40:60 to 10:90 (Sutton et al., 1980) resulted in variable reductions in milk and protein yields, and a greater decrease of about 40% in fat yield. The fall in fat content on maize diets was therefore less severe because of the simultaneous fall in milk yield as hay:concentrate ratio was reduced.

Table 17. Milk production in cows fed different ratios of hay:barley-based concentrates at a fixed digestible energy intake (after Sutton et al., 1980).

	Hay:concentrates ratio	
	40:60	10:90
Milk yield (kg d^{-1})	16.1	20.6
Butterfat (g kg^{-1})	44.9	20.6
(kg d^{-1})	0.73	0.42
Milk protein (g kg^{-1})	31.5	30.3
(kg d^{-1})	0.51	0.62

Although it is clear that hay:concentrate ratio is crucially important in affecting milk fat production, level of feed intake is also known to be important. This was clearly demonstrated in the experiment by Broster et al. (1979) which showed that milk fat content fell at each hay:concentrate ratio, when level of digestible energy intake was increased. As a result, it has been pointed out (Sutton, 1981) that no single concentration of roughage or fibre in the diet can be recommended for maintaining milk fat content, since the higher the level of feed intake, the higher the fibre content necessary to maintain a given fat content. However, it has been suggested that maintaining a concentrate:roughage ratio of 2:1 or less will often maintain adequate milk fat contents, though this will depend on the characteristics of roughage and concentrate, level of intake and method of feeding (Sutton, 1981).

There was no evidence from the experiments of Broster et al. (1979) or Sutton et al. (1980) that high barley:low hay diets increase milk protein content.

However, there is strong evidence (Balch, 1972) that general underfeeding causes depression of milk protein content, and that this is difficult to rectify if underfeeding is prolonged (Rook, 1976).

6.1.3.1 The use of buffers in cereal-rich diets

A variety of rumen buffers (e.g. sodium bicarbonate, magnesium oxide) have been used to try and increase rumen pH, though any response is now thought to be partly due to an increase in rumen dilution rate rather than pH (Sutton, 1981). With diets containing a low forage:concentrate ratio, sodium bicarbonate has been shown to increase milk yield and fat yield (Emery and Brown, 1961; Miller et al., 1965). Recent work has shown that feeding of sodium bicarbonate and sugars with silage can increase microbial protein synthesis (Newbold et al., 1988), but it does not necessarily increase feed intake (Newbold et al., 1989).

6.1.3.2 Metabolic problems resulting from cereal-rich diets

There are a number of problems additional to low milk fat contents which are associated with feeding high rates of rapidly fermented carbohydrates (such as finely processed wheat or barley) in large meals. The most severe of these disorders is metabolic acidosis, which can in severe cases lead to death, or chronic crippling diseases such as laminitis (Webster, 1987). It can also, through depression of appetite, result in ketosis. Although more common in intensively fed beef and sheep, there can also be a risk of bloat which results when eructation or belching is inhibited, resulting in a failure to expel the gases produced by rumen fermentation. To avoid these problems, it has been recommended that the feeding of 'starchy' concentrates should be restricted to a maximum of about 4 kg at a single feed (Webster, 1987), though this general rule will depend on the form of the concentrate and also on cow size.

It has been claimed that diets containing high proportions of cereal-based concentrates can increase the risk of laminitis (Manson and Leaver, 1989), though this has been disputed (G. P. David, Pers.Comm.).

6.1.3.3 Low cereal inclusion rate

It is generally accepted that increasing the inclusion rate of barley-based concentrates above about 60% of total diet DM tends to depress milk fat content and fat yield. However, the opposite appears to occur at relatively low rates of inclusion, at least on grass silage-based diets. Evidence of this is available from the two studies summarised in Table 18. It can be seen that supplementation with 4.7 kg DM of barley (Castle and Watson, 1976) or 4.3 kg DM of a cereal-based concentrate (Rae et al., 1986) increased milk fat content as well as milk yield, as compared with feeding grass silage alone. The calculated inclusion rates of concentrates were 35% and 29% of total diet DM in the two respective studies. The causes of these effects are not fully understood, but it seems possible that the cereal starch resulted in improved microbial efficiency through increased capture of silage nitrogen, as previously discussed in Section 3.0.

It is worth noting that there may also be substantial responses in milk production to low rates of protein supplementation (Thomas and Thomas, 1989). This is discussed further in Section 6.1.6.

Table 18. Effect of protein supplements on the performance of cows given ad libitum access to grass silage.

Supplement intake (kg DMd^{-1})	Silage intake (kg DMd^{-1})	Milk yield (kgd^{-1})	Milk composition (g kg^{-1})			Source
			Fat	Protein	Lactose	
None	10.8	14.6	41.9	29.0	46.9	Castle &
Barley (4.7[1])	8.6	16.1	45.0	30.1	46.8	Watson
Groundnut cake (1.5)	11.1	17.6	40.1	29.5	46.8	(1976)
Groundnut cake (0.8)+ barley (3.9)	9.3	17.9	42.3	31.0	46.8	
None	11.4	15.8	37.8	29.5	47.9	Rae et al.
Fishmeal (0.8)+ soyabean meal (0.4)	12.1	20.9	37.5	31.7	47.4	(1986)
Fishmeal (0.4)+ soyabean meal (1.1)	12.1	20.1	39.2	31.9	48.5	
Cereal-concentrate (4.3)	10.4	21.3	42.2	30.7	48.5	

1, Amount of supplement (kg DMd^{-1})

6.1.4 Comparison of cereal-based concentrates with other feedingstuffs for milk production

6.1.4.1 Molassed sugar beet pulp

Early work (Castle, 1972) with Ayrshire cows on hay-based diets showed that milk production was similar whether barley or dried molassed sugar beet pulp was fed in amounts up to approximately 8 kg DM per cow d^{-1}. Later studies with grass silage as the basal forage (Castle et al., 1981), similarly showed that for milk production, barley and beet pulp were interchangeable on a DM basis.

6.1.4.2 Fodder beet

There is some evidence that milk fat contents can be significantly increased when fodder beet is fed in place of barley (Krohn and Andersen, 1979). This is thought to be at least partly due to an increase in the ratio of rumen acetic plus butyric:propionic acids. There is also evidence that milk protein contents can increase when fodder beet is fed (Roberts and Martindale, 1990), though this may simply be due to increased DM and energy intakes.

6.1.4.3 Fibrous versus starchy concentrates

Over recent years, there has been a considerable research effort into the effects of concentrate composition on forage intakes and milk production. There has been a widely held belief that fibrous concentrates result in a reduced substitution rate compared with starchy (e.g. cereal-based) concentrates. However, Thomas and Thomas (1989) pointed out that data from both silage-based diets (Thomas et al., 1986) and hay-based diets (Sutton et al., 1987) indicate no differences in substitution rate due to concentrate type at concentrate inputs ranging from 6-12 kg DM per day. Although forage intakes tend to be higher with fibrous concentrates, this does not necessarily always apply. Thomas and Thomas (1989) summarised a number of studies with silage as the basal forage, and this summary is repeated in Table 19. Responses in milk yield and milk composition to fibrous concentrates are inconsistent, although there is some evidence to support an increase in fat content with high levels of concentrate input (e.g. Sloan et al., 1988), as has been shown with hay-based diets (Sutton et al., 1987).

This tends to be accompanied by a small reduction in milk protein content. In general, the response in milk fat and protein yields to replacement of starch with fibre tends to be small, provided the proportion of the supplement is less than 60% of total diet dry matter (Thomas and Rae, 1988).

Table 19. The response in silage intake, milk yield and composition to the substitution of starch with fibre-based supplements.

Fibre source	Amount of concentrate ($kg\ DMd^{-1}$)	Change in silage intake ($kg\ DMd^{-1}$)	Change in milk production: Yield (kgd^{-1})	Composition ($g\ kg^{-1}$): Fat	Protein	References
Molassed beet pulp	6.3	+0.5	+0.3	+3.2	+0.2	Castle et al. (1981)
	5.8	-0.1	+0.6	0.0	+0.7	
Unmolassed beet pulp (only 40% of total)	8.4	-0.2	-0.1	-1.1	-0.1	Mayne and Gordon (1984)
Unmolassed beet pulp, rice, bran, fat	6.0	+1.0	+2.1	-5.8	-1.0	Thomas et al. (1988)
	10.9	+0.8	+1.0	+1.0	-1.3	
Citrus pulp, sugar beet pulp	10.5	+0.2	-0.9	+4.3	-1.0	Sloan et al. (1988)

6.1.5 Sugar/protein supplementation

Fundamental studies have shown that benefits can result from supplementing grass silage with sugar rather than starch, as previously discussed in Section 3.0. This has recently been developed into a production study using autumn calving cows fed grass silage to appetite, together with one of four different supplements (see Thomas and Rae, 1988), and results are summarised in Table 20. Although the molasses and sodium bicarbonate supplement resulted in a substantially lower milk yield than the cereal-based concentrate, the molasses + sodium bicarbonate + protein supplement resulted in the highest milk yield with significantly higher milk protein content and milk protein yield. Interestingly, the butterfat content was highest on the cereal-based concentrate, which supports other studies where moderate amounts

of cereal-based concentrates have been fed with grass silage-based diets and produced increased milk fat contents (see Table 18).

Table 20. Effect of sugar, sodium bicarbonate and protein supplement on the dry matter intake and milk production of cows offered grass silage ad libitum (after Thomas and Rae, 1988).

	Silage intake (kg DM d^{-1})	Milk yield (kg d^{-1})	Milk composition (g kg^{-1})		
			Fat	Protein	Lactose
Cereal based concentrate (4.3)[1]	11.1	21.6	41.7	31.0	48.5
Fishmeal (0.4), Soyabean meal (1.2)	12.2	20.4	37.2	32.7	48.1
Molasses (1.6), Sodium bicarbonate (0.4)	12.0	17.8	40.9	31.8	48.5
Fishmeal (0.4), Soyabean meal (1.2) Molasses (1.6), Sodium bicarbonate (0.4)	12.4	22.5	38.2	32.4	47.7

1, Weights of supplement (kg DMd^{-1}).

6.1.6 Protein supplementation

Although beyond the scope of this review, the subject of protein supplementation is clearly extremely important. Thomas and Rae (1988) in a review of concentrate supplementation of silage have pointed out that increasing the proportion of protein in the concentrate has often resulted in an increase in diet digestibility and in silage intake. The low efficiency of microbial protein synthesis on silage only diets has been discussed previously, but this is at least partly explained the substantial responses in milk production to protein supplements, as shown in Table 18. A recent study (Poots and Unsworth, 1990), using high quality grass silage as the basal forage, showed substantial increases in silage dry matter intakes and

milk production to the supplementation of barley with soyabean meal and fish meal. Silage DM intake, milk yields and quality were also superior in cows fed 2.5 kgd^{-1} of a high protein (340 g kg^{-1}) supplement compared with feeding 4.5 kgd^{-1} of a low protein (100 g kg^{-1}) barley/molasses-based supplement.

6.2 Growing cattle and sheep

6.2.1 Effect of cereal species

Some comparisons of the different cereal species have been carried out mainly in intensive diets based predominantly on cereals.

6.2.1.1 Beef cattle

Kay et al. (1972b) compared pelleted diets containing whole barley, whole maize, whole oats and whole wheat fed to Friesian steers from 100 to 400 kg live weight. The diets containing maize and wheat were also supplemented with 15% oats to minimise the risk of digestive upset. There were no significant differences in either DM intake or liveweight gain between steers on any of the treatments (liveweight gains ranged from 1.12 on wheat to 1.27 kgd^{-1} on maize). However, there were marked differences in feed conversion efficiencies which ranged from 4.7, 5.2 and 5.5 kg feed DM per kg liveweight gain with maize, wheat and oats respectively. The inclusion of some oats in the wheat and maize diets may have influenced the DM intakes achieved, since, when a ground maize-concentrate mixture containing no additional fibre was fed to steers, dry matter intake was only 81.0 compared with 90.0 g kg^{-1} metabolic live weight for a ground barley-concentrate mixture (Kay and MacDearmid, 1973).

Studies in the United States comparing wheat and barley-based rations for steers have shown no significant differences between them in daily liveweight gain or feed conversion efficiency, although feed intakes were significantly lower on barley (Garrett et al., 1968). There is also evidence from the United States that wheat may be best utilised when fed in combination with maize or milo rather than as the sole grain (Brethour, 1970). However, it appears that such a benefit does not result from mixing wheat with barley, so it is probably of little relevance in the UK. Experience in the United States also suggests that there are significant differences between wheats.

Acidosis problems are reported to be more widespread when feeding hard red compared with soft wheat varieties (Eng, 1984).

6.2.1.2 Sheep

Ørskov et al. (1974a) compared barley, maize, oats and wheat fed to lambs either whole and loose or ground and pelleted. The main results are summarised in Table 21. The diets based on oats supported significantly lower liveweight gains and were utilised less efficiently than those based on the other cereals. In relation to this poor performance of the oat-based diets, Webster and Povey (1990) stated that oats are unsuitable for feeding to early-weaned lambs.

Concentrates based on whole wheat and whole barley have also been compared as supplements to straw for ewes in the final weeks of pregnancy and produced a similar prformance (P. Kelly, Pers.Comm.). No digestive upsets resulted from either the whole wheat or barley-based concentrates.

Table 21. Effect of different cereals and processing on feed utilisation by lambs (Ørskov et al., 1974a).

Cereal	Form	Liveweight gain ($g\ d^{-1}$)	FCE ($kg\ DM\ kg\ gain^{-1}$)
Barley	Ground pelleted	347	2.8
Barley	Whole loose	340	2.8
Maize	Ground pelleted	346	2.6
Maize	Whole loose	345	2.5
Oats	Ground pelleted	238	3.3
Oats	Whole loose	241	3.1
Wheat	Ground pelleted	323	2.6
Wheat	Whole loose	303	3.0

6.2.2 Cereal inclusion in diet

Commercially, the use of cereals in diets obviously depends very much on their costs relative to other feeds. The importance of cereals as

feedingstuffs varies enormously between different production systems, but can also vary considerably within an individual system. Discussion is restricted to two contrasting situations:

(a) High cereal inclusion (approximately 90% of total diet DM), as found in intensive cereal production of beef and sheep; and

(b) low to moderate cereal inclusion (up to approximately 40% total diet DM), as is usually found in efficient grass and grass silage-based production systems.

6.2.2.1 High cereal use - Intensive cereal finishing

6.2.2.1.1 Beef cattle

This is the system developed at the Rowett Research Institute in the early 1960s (Preston et al., 1963) in which cattle are fed a cereal-based diet to appetite from about 12 weeks old to slaughter at 10 to 12 months old. The economics of this system depend heavily on calf and cereal prices (Crabtree, 1988). Performance standards are summarised in Table 22. In the UK, barley is the most widely used cereal on this system, since there is considerably less risk of digestive upset with barley compared with wheat (Kay, 1975). Minimal cereal processing (i.e. cracking/rolling) and access to long forage (usually straw) are extremely important to minimise the risks of acidosis and bloat. The use of feed additives such as monensin sodium or avoparcin are known to improve feed conversion efficiency, and to reduce the risk of bloat on intensive diets (MacGregor, 1983). Because of the heavy reliance on cereals, adequate protein supplementation is important. In commercial practice, diets with crude protein contents of 160 g kg^{-1} fed to about 200 kg live weight, decreasing to 120 g kg^{-1} above 350 kg live weight are often suggested (ADAS, 1987a), though there is evidence that a single diet containing 140 g kg^{-1} crude protein can result in equally satisfactory performance (I. Rigby, Pers. Comm.). Crude protein standards are known to be inadequate and a detailed discussion of the nutrient requirements for intensively fed cattle has been given by Newbold (1987).

Over recent years, a system of intensive cereal finishing of weaned suckled calves has been successfully developed at ADAS High Mowthorpe, with liveweight gains of 1.5 to 1.9 kgd^{-1} being achieved by bulls (Rigby et al.,

1988). Rolled barley has comprised about 85% of the concentrate fed. Crude protein contents of up to 140 g kg^{-1} have been shown to be justified on this system (Jacklin and Rigby, 1990).

Table 22. Targets for Friesian bulls on intensive cereal finishing (ADAS, 1987a)

Slaughter weight (kg) full (i.e. on the farm)	440
fasted (i.e. market)	420
Age (months)	10-12
Daily liveweight gain (kg)	1.3
Cold carcase weight (ex KKCP) (kg)	235
Killing out % - full weight	53.5
- fasted weight	56.0
EEC carcase classification (conformation/fat)	0+/3
Performance from three months to slaughter:	
Feed conversion (kg feed:kg gain)	5:1
Compound feed use (kg)	1720

6.2.2.1.2 **Sheep**

Intensive cereal diets can also be fed successfully to lambs, and most of the basic principles relevant to cattle are applicable. However, it is recommended that whole rather than processed cereals are fed to lambs to minimise the risks of acidosis and rumenitis, and to avoid the production of soft carcase fat (Ørskov et al., 1974b). Ørskov (1983) provided a review of

lamb nutrition from birth to slaughter, and more recently Webster and Povey (1990) reviewed the nutrition of finishing lambs.

6.2.2.2 Low/moderate cereal use

Cereal-based concentrates are commonly used to supplement forage-based diets for cattle and sheep. There are a number of recent reviews which have considered the potential and limitations of grass for sheep (Speedy and Bazely, 1987; Treacher, 1990) and cattle (Baker, 1988), and of silage for sheep (Appleton, 1987) and for beef cattle (Steen, 1988; Thomas and Gill, 1988). Comprehensive discussion of this subject is not possible here, but essentially animal production from forage-based diets depends firstly on the forage itself, and secondly on the level and type of concentrate supplementation. In commercial practice, the main factors influencing concentrate supplementation are the animal performance required and the amount and quality of forage available. Relative costs largely dictate which concentrates to feed.

6.2.2.2.1 Practical examples

The silage bull beef system developed by ADAS, Rosemaund (see Hardy and Meadowcroft, 1986) is a good example of an intensive forage-based system supplemented with limited quantities of concentrates (usually cereal-based). It relies on good quality grass silage, typically supplemented with 2 to 3 kg of concentrates per bull d^{-1} to support liveweight gains of 1.0-1.1 kg d^{-1}, from three months old to slaughter at about 15 months old.

High quality grass silage can also be fed with little if any concentrate supplementation to successfully support twin-bearing ewes in late pregnancy, but more usually some supplementation is necessary (Apolant and Chestnutt, 1982; ADAS, 1983). As discussed in Section 3.0, it is worth considering that at even a low rate of cereal or other carbohydrate source (0.2kg per ewe d^{-1}), a significant amount of fermentable metabolisable energy will be provided and this may increase microbial protein synthesis.

6.2.2.2.2 Response to concentrates

This is known to vary depending particularly on the amount of concentrates fed and on forage quality.

Steen (1988) has summarised the review of Drennan (1984), which quantified the response in performance of finishing steers to concentrate supplementation of silage-based diets. When concentrate input increased from 0 to 1.8 kg d^{-1} (19% of DM intake), liveweight and carcase gains were increased by 147 g and 91 g kg^{-1} concentrate respectively. When concentrate input was increased from 1.8 to 3.6 kg d^{-1} (19 to 34% of DM intake) corresponding increases were 63 and 52 g kg^{-1} of concentrate.

The interaction between silage digestibility and the response to supplementary concentrates has been examined in a number of experiments with steers (Steen, 1984; Drennan, 1986). In general terms, as silage quality increases, so the response to concentrates decreases. Steen (1988) reported that as silage digestible organic matter content of the DM (DOMD) increased by 85 g kg^{-1}, so the response in carcase gain decreased from 106 to 72 g kg^{-1} concentrate.

6.2.2.2.3 Alternative approach

The conventional means of overcoming the limitations of forage is to supplement with increasing amounts of concentrates (often cereal-based). Thomas and Gill (1988) have questioned this approach on silage-based diets because firstly, concentrates partly replace rather than supplement silage, and secondly, the advantages of making silage of high DOMD contents and high intake characteristics are generally reduced if the silage is then fed with starch or fibre-rich supplements. Because of this, recent research has concentrated on alternative strategies which involve the use of specific supplements to overcome the limitations in nutrient supply, without depressing silage intakes. The principles of using sugar and protein supplements have previously been discussed in Section 3.6, but the influence of these supplements on liveweight and carcase gains, and body composition, have not yet been established.

6.2.3 Comparison of cereals with other feedingstuffs

A wide range of different feedingstuffs has been compared with cereals and cereal-based concentrates for beef and sheep. Just two important examples have been chosen for brief consideration.

6.2.3.1 Roots

Although roots are of low DM content, this DM is highly digestible, so that the ME value of all roots is high and often comparable with barley grain (ADAS, 1987b).

Kay et al. (1972a) compared diets for Friesian steers containing varying proportions of roots and barley-based concentrates, ranging from 100% concentrates to 100% swedes, or 87% potatoes on a dry matter basis. The overall digestibility of dry matter was unaffected by diet, and liveweight gains were similar across all diets. However, when steers weighed less than 350 kg live weight, dry matter intakes were lower on 100% swedes than on concentrates.

A number of studies has been carried out using fodder beet for beef cattle (e.g. Hardy, 1980; MacDearmid and Kay, 1977) and for sheep (Brown, 1978-86). Crabtree (1985) provided a useful summary, and more recently Roberts and Martindale (1990) reviewed animal production studies with fodder beet. It is worth pointing out that an intensive beef system (called fodder beef) which relies mainly on fodder beet has been successfully developed at ADAS Gleadthorpe. This may prove to be a satisfactory alternative to the use of cereals.

6.2.3.2 Maize gluten feed (MGF)

This feed has been widely used over recent years for beef and sheep as well as for dairy cows. It is used in practice as a cereal replacer of high protein content (200 g kg^{-1}).

Some studies have been carried out comparing MGF with barley-based concentrates, as a major component of intensive beef rations. Keane and Drennan (1988) compared MGF and barley in all-concentrate diets ranging from all MGF to all barley plus soyabean meal for finishing steers. There were no significant differences in liveweight gain or carcase weight between the rations, but feed dry matter intakes increased with increasing MGF, so that feed conversion efficiency was significantly lower on the all MGF diet compared with the barley plus soya diet. Pullar (1991) compared all-concentrate diets for Charolais X Friesian bulls from 20 weeks of age to slaughter. A barley-based (850 g kg^{-1}) concentrate plus protein supplement

was compared with a barley (565 g kg^{-1}) plus MGF (400 g kg^{-1}) concentrate, and the same liveweight gain of 1.45 kgd^{-1}, was supported by both rations. In contrast to Keane and Drennan (1988), feed conversion efficiency of the diet containing MGF was superior to that of the barley-based ration (3.7 vs 4.2 kg DM kg^{-1} liveweight gain).

It has also been reported that MGF has been successfully used to replace barley-based concentrates for ewes in late pregnancy (P. Kelly, Pers.Comm.), but scientific data are sparse. Recent data from ADAS Redesdale indicate that MGF can be successfully used with barley to supplement baled silage in finishing rations for hill lambs (B. Merrell, Pers. Comm.).

6.3 Cereals in compound feeds

Cereal use in ruminant compound feeds is limited by price to the high energy/high quality products. The cost per unit of energy and protein has not been competitive in recent years relative to vegetable oils, oilseed meals and cereal by-products. Cereal use has, therefore, been limited to specific feedstuffs such as high energy dairy feeds, calf starter and lamb creep feeds and high energy beef and sheep finishing feeds.

7.0 RECOMMENDATIONS FOR RESEARCH

The following areas have been identified as requiring further research. They have been prioritised as very high, high and moderately high.

Very high priority

i. Study the factors influencing the measurement of DM, starch and protein degradation in the rumen using the nylon bag method.

ii. Determine the influence of factors such as protein content and processing/treatment methods on rate and extent of cereal protein and starch degradation in the rumen.

iii. Study the influence of variety within cereal species on the rate and extent of starch and protein degradation in the rumen.

iv. Investigate treatments and processing methods for their ability to

manipulate the rate and extent of starch and protein degradation in the rumen.

v. Study the effect of low rates of cereal supplementation to grass silage-based diets on ration digestion in the rumen, rumen metabolism and animal production.

High priority

i. Define the influence of agronomic factors such as fertiliser use on cereal protein content and quality for ruminants.

ii. Undertake animal production and metabolism studies into the use of high rates of cereals in diets for dairy cows and growing cattle. Emphasis should initially be put on the use of wheat.

Moderately high priority

i. Investigate the effect of grain treatments such as sodium hydroxide on grass silage intake, milk production and rumen metabolism.

ii. Investigate the effect of diets containing cereals of high oil content (oats and naked oats) on rumen digestion and metabolism and on the fatty acid composition of milk and body depot fat.

iii. Further measurements <u>in vivo</u> of the ME content of cereals including those of low specific weight and the development of accurate and rapid laboratory methods for predicting ME content.

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SECTION 2

CEREAL GRAIN BY-PRODUCTS

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1.0 INTRODUCTION

With the ruminant's greater ability to utilize fibre, through the rumen microbial action, many cereal by-products have considerable potential in ruminant feeds (Boucqué and Fiems, 1988). This may enable by-products to have an important sparing effect on the use of cereals.

Many of the conventional by-products have been used for some time, though new products will emerge with changing production methods. The extent of their use in ruminant diets will depend on their price (including transportation), together with their suitability for non-ruminants or other potential uses.

The classification of cereal by-products can be done in various ways, but by industry of origin has been chosen in this review to include milling, brewing, distilling and starch manufacture.

Rice and maize by-products are excluded from this review.

2.0 THE PRODUCTS

2.1 Milling by-products

In addition to the by-products listed below, cereal pellets and biscuit confectionery waste are also used in low amounts. The cereal pellets may be formulated to give a similar declared analysis to cereals, although their nutritive value may be rather less due to increased ash and fibre levels. Barley meal, however, is defined in the Feedingstuffs Regulations (Anon, 1991a) to contain not less than 96% pure barley.

Although biscuit meal is fairly commonly used in compound feed formulations, other bread/confectionery/breakfast cereals make only a small contribution as feedstuffs for ruminants.

2.1.1 Wheat offals

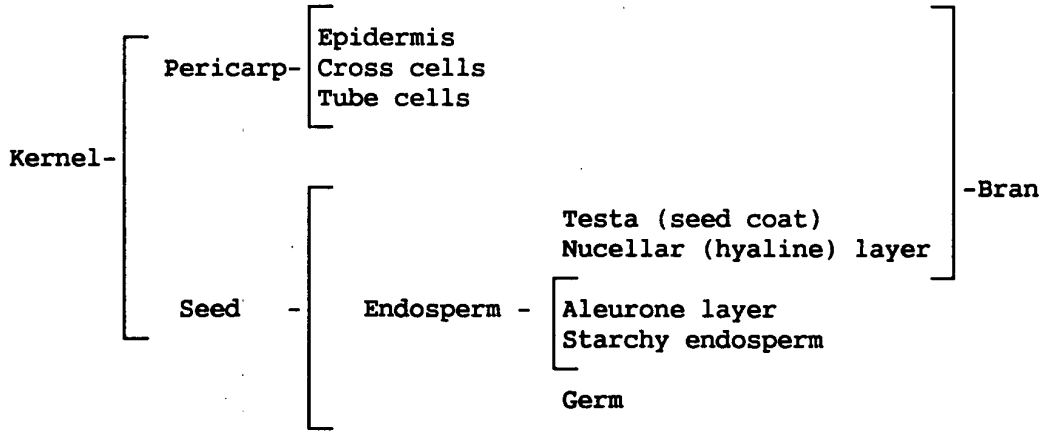
Wheat offals are the residues of flour milling, and range from the husk and bran to a fine residue, which is mainly endosperm with a limited amount of bran (Figure 1). Alternative names encountered are middlings, sharps, thirds, shorts and red dog. The grading is often made on the basis of

particle size. Offals may be sold as specific products or as a mixture. Wheatfeed, pollards and mill run may be names for combinations of individual components (Kent, 1975).

Wheat offals account for some 28% of the whole grain. As described by Kent (1975), wheat offals can comprise bran (14%), middlings (12.6%), shorts (0.3%) and red dog (1.1%).

The wheat germ is principally the germ of the grain with some fragments of the endosperm and the outer wheat skins. It is not available in substantial amounts as an animal feedstuff.

Figure 1. Outline of the components of cereal grain (after Kent, 1975).



Comparable products to wheat offals originating from other cereals include oatfeed millings, barley middlings, ryefeed and ryebran.

2.1.2 Oat by-products

Oat dust and meal seeds are principally used as animal feed. Oatfeed meal/pellets consist of a proportion of the oat husk added to the dust and meal seeds (70, 20, 10% respectively) (Kent, 1975) and hence have a lower feeding value. The Feedingstuffs Regulations (Anon, 1991a) indicate that this product should have a maximum of 270g kg^{-1} of crude fibre.

2.1.3 Grain screenings

Grain screening are the residues from the cleaning, storage and shipment of various cereal grains. They may be available as screenings from a single cereal or from mixed cereals. Imported grain screenings may contain a

proportion of rice, maize, sorghum and soyabean screenings. The type of grain, harvesting conditions and the timing of collection will all affect their nutritive value. Dry grain will be more brittle and older grain may have a greater content of mould and mould spores and hence a greater risk of mycotoxins being present (MAFF, 1985). Rancidity can also be a problem in batches of screenings which have a high oil content. Dustiness and impurities (e.g. soil, chaff and weed seeds) may have an adverse effect on palatability and animal performance (MAFF, 1985). Grain screenings are also often ground and added to milling offals (MAFF, 1985).

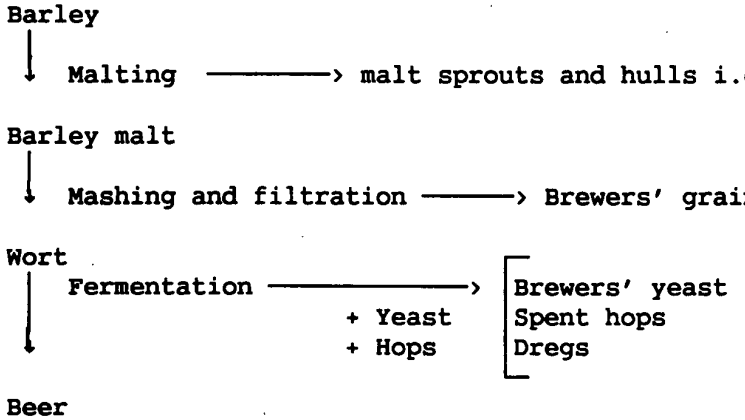
2.2 Brewery by-products

The major brewery by-products are discussed below. Further products include the spent hops, waste beer and brewers' yeast. Spent hops have high fibre and low digestibility and are of limited use as a feed, except at times of forage shortage. A low proportion of spent hops may be included with dried brewers' grains (Boucqué and Fiems, 1988). Waste beer has a low dry matter (DM) content, but can be a reasonable energy source.

Brewers' yeast is not normally used alone as a feed for ruminants, but may be incorporated with other by-products, particularly dried brewers' grains, at a 5% inclusion rate (Boucqué and Fiems, 1988).

A flow diagram of by-product production during brewing is shown in Figure 2.

Figure 2. Flow diagram of by-products from brewing (after Boucqué and Fiems, 1988).



2.2.1 Brewers' grains

Brewers grains originate from the brewing, malt beverage and malt vinegar industries. In the brewing process, malting barley is steeped in water and enzymic activity starts to convert the starch into sugar. The germinating barley is then kilned to stop germination (ADAS, 1982). The kilned malt, excluding the dried roots (malt culms) is then mixed with hot water in the mash tun. Some additional unmalted cereal may be added to the mash from which a sweet wort is produced. The residue is washed with hot water, becoming spent grains. Once the sweet wort has been boiled with hops, sugar and tannins, the protein-rich fraction (trub) coagulates and is generally added back to the spent grains to produce brewers' grains (Wainman et al., 1984).

In addition to the variability arising from the brewing processes, many variations in the amount and characteristics of the ingredients used are possible. Geographical variations may also be involved (MAFF, 1983). Wainman et al. (1984) suggested that Scottish breweries use malt from Scottish barley of higher nitrogen content, and tend to produce more brewers' grains per tonne of malt used. Whether this remains the case is unclear.

2.3 Distillery by-products

Malt and grain distilleries produce a range of wet and dried by-products which may be used by the animal feed industry. Malt distilleries use barley to produce malt whisky. Historically, grain whisky distilleries in Scotland used maize as the cereal source, although wheat is now increasingly used (Anon, 1992).

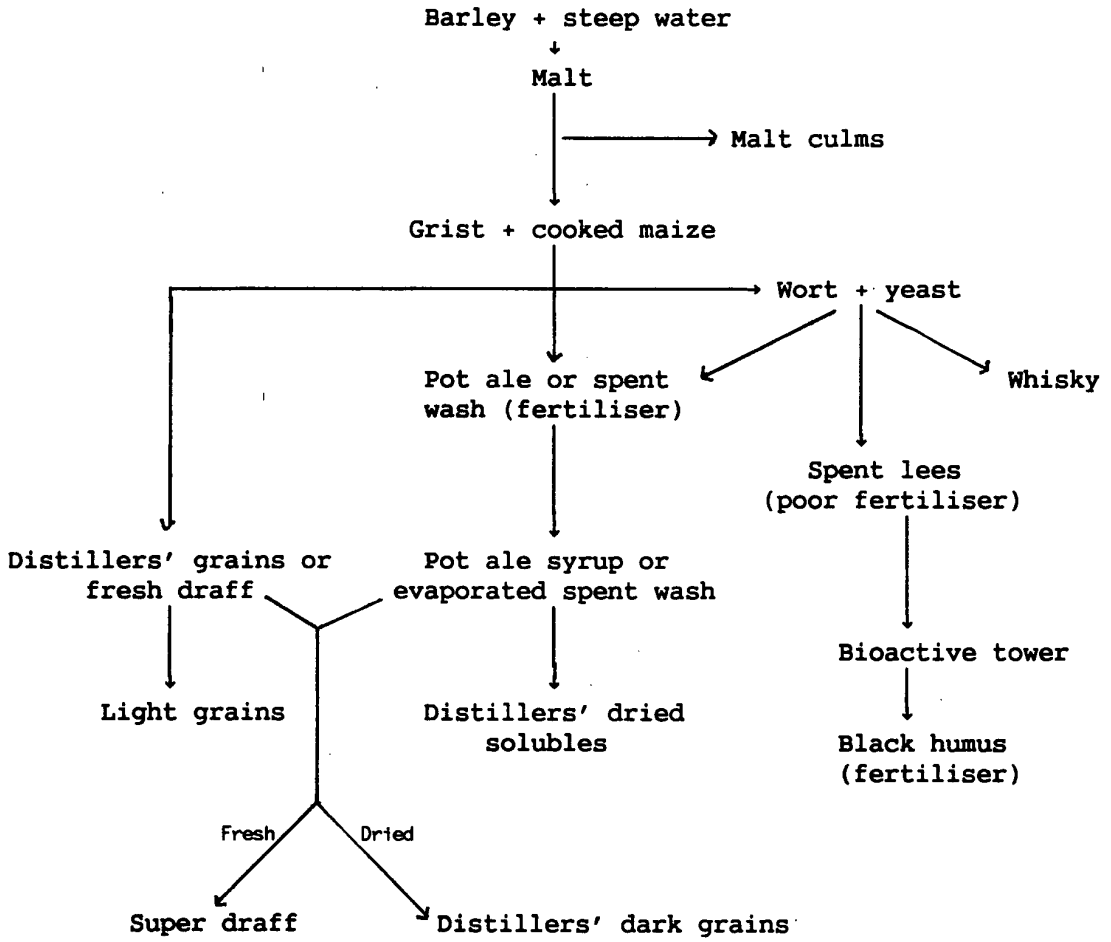
In addition to the by-products considered below, some malt culms and malt residual pellets are available for feeding to ruminants. Malt culms are the dried rootlets of malted barley. They have a relatively high crude protein content which is of limited value, due to a low true protein content, and a high content of the amino acid asparagine, which imparts a bitter flavour (Black et al., 1984). The inclusion of malt culms in diets is therefore limited. Malt culms have also been used to a limited extent as a silage

absorbent, due to their high absorption capacity.

Malt residual pellets consist of heat sealed pellets combining the malt culms, barley dressings (thin and broken grains) and barley husks/dust, in approximately equal proportions.

The production of distillery by-products from barley is shown in Figure 3. By-product production from other cereals follows a similar scheme.

Figure 3. Production of distillery by-products (after Black et al., 1984).



2.3.1 Draff (distillers' wet grains)

Draff is the spent grain residue after extraction of the malt or malt plus cooked cereal. Draff may be sold directly or processed by pressing or drying.

'Supergrains' is a specific wheat-based draff product from one grain distillery producing grain whisky and neutral grain spirit. It contains yeast residues in addition to the insoluble parts of the grain from the mashing and fermentation processes (Offer, 1990).

2.3.2 Distillers' light grains or dried draff

Dried draff has a similiar nutritive value to draff, but is very rarely produced now. Dried draff or pressed draff have been considered as absorbents, though their ability to control effluent from bunkers of grass silage has been variable or poor (Offer and Al-Rwidah,1989).

2.3.3 Pot ale syrup

Pot ale syrup (PAS) is the liquor residue from the first distillation in whisky production, which is condensed into a syrup. Strictly speaking, PAS comes from malt distilleries and evaporated spent wash (ESW) is produced by grain distilleries. Both products are usually known as PAS. This syrup may be dried to produce distillers' dried solubles or mixed with draft and dried to form distillers' dark grains.

2.3.4 Distillers' dried solubles

Distillers' dried solubles are the result of evaporating PAS or ESW, which then has lime added prior to its final drying. The product is a light, free flowing powder with an attractive smell. It is unsuitable for use as a straight feedingstuff due to its dusty nature, but it can be pelleted. It is used primarily as a feed for non-ruminants, but it is also claimed to help stimulate the activity of rumen microflora (Black et al., 1984).

2.3.5 Super draff

Super draff is a mixture of varying amounts of draff and PAS or ESW (usually in the ratios of between 4:1 and 2:1). It resembles draff but is stickier and has a relatively short storage life unless treated with a mould inhibitor. Its nutritive value depends on the proportions of the two by-products included, but is similiar to distillers' dark grains (NOSCA, 1982). Production will be influenced by drying costs. It is sometimes referred to as 'Maltifeed'.

2.3.6 Distillers' dark grains

Distillers' dark grains (DDG) are a dried mixture of draff and PAS or ESW, normally in the ratio of 2:1 on a DM basis. Malt distilleries produce malt DDG from barley, whereas the product from grain distilleries, using wheat or maize, is referred to as grain or maize DDG (Black et al., 1984). These products are very palatable to livestock and are widely used in compound feed manufacture and as straight feedingstuffs on farms. There may be considerable differences in the colour and physical form (pellet or meal) of DDG from different origins.

2.4 Starch and glucose manufacture

During starch production, wheat is milled, wetted and separated into starch, wheat gluten and a wet fibre-rich product. The latter two materials are generally combined to form wheat gluten feed. Wheat gluten feed may also contain the steeping liquor and some of the germ. Wheat gluten can itself be a by-product leaving wheat starch slurry (200-300g kg^{-1} DM) as a residue (Boucqué and Fiems, 1988).

Glucose filtrate is a product resulting from invert sugar extraction from wheat and maize flour and has the appearance of a moist meal (Nutrition Trading (International) Ltd., 1990).

Barley fibre is a by-product from integrated starch-ethanol production, and is similiar in nutritive value to maize gluten feed (Huhtanen, 1992).

2.5 Quantities of by-products used

The quantitities shown in Table 1 indicate the total use of cereal by-products (MAFF, 1992) and no division between compounders, feed/livestock companies and farmers has been made. The approximate proportion of certain by-products fed to ruminants is also given in Table 1.

The use of wheat brans in the European Community (EC) has remained fairly stable, averaging 6.3% of the total livestock feed use between 1984 and 1991 (FEECON, 1991). In the UK, wheatfeed accounted for approximately 25% of all the wheat by-products used by compound feed manufacturers in 1989 (Anon,

1991b). No breakdown of the distillery by-products into cereal of origin is possible.

Table 1. Total use of by-products (x 10^3 t) and percentage fed to ruminants (after MAFF, 1992).

	Total use					% fed to ruminants
	1987	1988	1989	1990	1991	
Imported						
Wheat offals	na	135	104	129	100	40
Grain screenings	88	19	13	9	5	na
Distillery wastes	217	120	91	157	124	na
Home produced						
Wheat offals	1067	1157	1076	999	969	40
Oat offals	53	61	78	85	79	45
Distillery wastes:						
- sold wet	83	108	74	89	na	na
- as dark grains	114	126	112	110	na	na

na = figures not available

The total amount of brewers' grains fed to livestock in the UK is approximately 1 million t, the majority of which is fed wet (i.e. fresh or ensiled) (Ms. S. Scarret, Brewers' Society, Pers. Comm.), with some dried grains used by compound feed manufacturers.

The quantities of home-produced grain screenings, malt culms, biscuit and confectionery waste are not available.

3.0 FEED EVALUATION AND NUTRITIONAL ASPECTS

Cereal by-products vary widely in their energy content, from values higher than the original cereal to considerably lower (MAFF, 1990). Compared with the original cereal, there is also a marked change in the form in which the energy in the by-product is supplied. In general, starch and sugar levels are reduced compared with the parent cereal and amounts of fibre and oil are

increased. For wheat, comparative values are shown in Appendices 8.1-8.3. The digestibility of fibre is influenced by the degree of lignification which in turn will have a marked effect on the energy level (Van Soest, 1982). Protein digestibility and degradability are influenced by the processing the particular product has undergone.

3.1 Milling offals

The chemical composition and nutritive value of wheatfeed, offals and middlings have been reported in the UK Tables of Nutritive Value and Chemical Composition (MAFF, 1990). The values shown in Appendix 8.1 omit middlings (due to limited data), but compare wheatfeed and offals with wheat bran and grain. The higher fibre and lower starch concentrations in the by-products are reflected in the lower organic matter digestibility and metabolisable energy values. Phosphorus and magnesium concentrations are considerably higher than in the original grains.

The protein quality of milling by-products has received limited attention. As can be seen from Appendix 8.1, the protein content of the wheat by-products is typically some 30% higher than the original grain. In terms of amino acid composition, wheat offals are slightly deficient in lysine and methionine (Church, 1984).

3.1.1 Wheat offals

The nutritive value of wheat offals can vary widely depending on the proportion of husk, bran, germ and endosperm present. A classification in terms of protein, fat and fibre was made by Church (1984) and is given in Table 2.

The starch comes almost entirely from the endosperm and lipid and protein contents increase as the proportions of germ and bran increase (Kent, 1975). Although the original cereal from which the offals are derived will influence the composition, in practice many batches of cereals will be combined together, and the type of soil, fertilizer treatment, climate, variety and storage for the individual crops will have limited influence on the analysis. Rancidity can be a problem unless the product is pelleted (MAFF, 1985).

Table 2. Specifications of wheat offals (g kg^{-1}) (after Church, 1984).

Fraction	Minimum protein	Minimum fat	Maximum fibre
Bran	135-150	25	120
Middlings	100-140	30	95
Bran + middlings	140-160	20	95
Shorts	140-160	35	70
Red dog	135-150	20	40

3.1.2 Biscuit meal

Biscuit meal is normally a high energy feed, with a variable but usually high fat content (Vitec, 1989). Biscuit meal consists primarily of wheat flour, with salt, sugar and fat added. The digestibility of the protein may be reduced by the baking and drying processes. Oxidative rancidity of the fat in poorly stored biscuit waste can increase the dietary vitamin E requirement. The absorption of moisture can lead to moulding and hence increase the risk of the presence of potentially damaging levels of mycotoxins (Vitec, 1989).

3.1.3 Oat by-products

Kent (1975) has given the typical chemical composition of oat by-products (Table 3). Information on the quality of the protein in oatmeal by-products is limited.

3.2 Brewery by-products

3.2.1 Brewers' grains

Brewers' grains contain only limited quantities of soluble carbohydrates, but

Table 3. Chemical composition of oatmeal by-products (all as g kg^{-1}) (after Kent, 1975).

By-product	Crude protein	Fat	Ash	Crude fibre	Starch
Oat husk	13	4	43	361	9
Oat dust	100	45	60	216	100
Meal seeds	79	35	28	172	264
Oat feed meal	34	15	37	300	57

have a high protein and fibre content. The composition will depend on the ingredients of the original grist, the efficiency of starch hydrolysis and extraction, and the amount of liquor retained once the sweet wort is removed (ADAS, 1982).

The chemical composition, digestibility and energy values for brewers' grains derived from the UK Tables of Nutritive Value and Chemical Composition (MAFF, 1990) are given in Appendix 8.2. The fat content of brewers' grains is double that in the original barley grain, and has a high concentration of unsaturated fatty acids which could depress fibre digestion in the rumen (Miller et al., 1970). Brewers' grains are low in minerals, particularly in sodium and potassium, but also in certain trace elements and vitamins (Lewis and Lowman, 1989). They may require a high level of mineral and vitamin supplementation when included in diets at high proportions.

In a study undertaken by ADAS in co-operation with Associated Brewery Trades Association (ABTA), samples of brewers' grains that had been ensiled for at least four weeks were taken from 177 silos. The mean oven DM content was 283 g kg^{-1} (ADAS, 1985).

Studies at the Feed Evaluation Unit, ADAS Drayton, suggest that volatile components account for 6% of the toluene DM, equivalent to a difference between the oven and toluene DM contents of 17 g kg^{-1}. Energetic evaluation of samples of fresh and stored brewers' grains produced a mean metabolisable energy value of 10.4 MJ kg^{-1} DM (ADAS, 1982).

The relationship of Blaxter and Clapperton (1965) for predicting methane energy loss was studied by Wainman et al. (1984) using sheep fed Scottish brewers' grains. This was due to concern over the accuracy of the relationship when applied to brewery and distillery by-products. In the six samples studied the methane energy loss was indeed lower than would have been predicted (0.041 and 0.076 of gross energy; measured and predicted respectively). The resulting mean metabolisable energy value was 11.7 MJ kg^{-1} DM. In advisory practice, ADAS uses a prediction equation based on neutral detergent fibre content to calculate the metabolisable energy content, using a correction for volatile components of 4g kg^{-1} (Wainman et al., 1984).

Some liquor is lost from brewers' grains during storage, although the chemical composition, digestibility and energy content remains similiar to that of the fresh grains (Huhtanen, 1992). Boucqué and Fiems (1988) do, however, refer to a small reduction in organic matter digestibility from 64.4 to 62.7% following ensiling.

Only limited information is available on the protein degradability of wet brewers' grains. Dried brewers' grains contain relatively less soluble protein (Boucqué and Fiems, 1988). Merchen et al. (1979) using cannulated steers showed that dried brewers' grains were reasonably resistant to rumen degradation, with the amounts of non-ammonia nitrogen reaching the abomasum being higher than when urea or soyabean meal were fed. An effective protein degradability value of 0.49 (at an outflow rate of 0.08 h^{-1}) was given by Van der Honing and Alderman (1988).

3.3 Distillery by-products

The chemical composition, digestibility and energy values of the distillery by-products are given in Appendix 8.3 derived from the UK Tables of Nutritive Value and Chemical Composition (MAFF, 1990). The composition of draff is compared with brewers' grains in Appendix 8.2.

The limited analysis available for Supergrains would suggest that they are similiar to brewers' grains or draff, with the exception that the protein and oil contents are higher (Offer, 1990). Appendix 8.3 gives the limited chemical composition data available for malt culms. No metabolisable energy

value is available from the source quoted, although the digestibility measured *in vitro* was low.

The main distillery by-products are discussed in the following sections.

3.3.1 Distillers dark grains

The distillery by-products vary in chemical analysis and nutritive value depending on the type of distillery and the malting/extraction processes, rather more than between distilleries of the same type. Malt and grain DDG both have relatively high energy contents, despite high fibre levels (ADAS, 1988). Maize DDG may have a slightly higher energy content due principally to a higher oil and lower fibre and ash contents. Heat is involved in processing, and overheating can affect digestibility. Cell walls of heated feeds appear to have a higher lignin content than those unheated due to the production of soluble lignin-like products. These products can arise as a result of the Maillard reaction and may reduce both the digestibility of cell wall and non-cell wall components (Van Soest and Mason, 1991).

Acid detergent insoluble nitrogen (ADIN) analysis has been used for describing the unavailable protein fraction (Van Soest, 1982). Weiss *et al.* (1989) questioned the usefulness of both ADIN and NDF analysis in relation to DDG on the basis of studies with dairy cows which compared DDG with soyabean meal. A re-examination of the data of other workers who have challenged the use of ADIN for DDG was undertaken by Van Soest and Mason (1991); this showed that about 0.6 of the ADIN in DDG appeared to be digestible. Further work is needed to clarify the use of ADIN analysis for estimating unavailable protein in DDG.

Both in the UK and in the USA there has been a degree of preference for lighter coloured DDG due to the belief that the lighter colour is indicative of limited heat damage. The protein degradability values given in Appendix 8.3 suggest that wheat DDG have a high degradability, even in comparison with limited data on maize DDG (ADAS, 1989). The high degradability stems entirely from a very high immediately soluble nitrogen fraction. Further work is needed to determine whether the high solubility value measured, using nylon bags, is a true solubility or due to loss of fine particles through the bag pores.

Five samples of grain and malt DDG were studied by Wainman et al. (1984) and these showed lower methane energy losses than predicted from the Blaxter and Clapperton (1965) equation. This has been suggested as being possibly due to the low starch and sugar content of DDG. These findings are similar to those of ADAS (1988). This low starch/sugar content is an important consideration in relation to DDG replacing cereals in diets.

In digestibility studies with wether sheep, where malt and grain DDG have been fed with double their own weight of dried grass, very high digestibilities were obtained. It was suggested that either the calcium in the dried grass may help to avoid the depressing effect on fibre digestion of the fat in the grains, or the additional protein in the grains enhances digestion of the dried grass (Black et al., 1984).

The copper content of home produced grain and malt DDG is generally high, at approximately 40-50 mg kg^{-1} DM (Black et al., 1984). This can limit their use as a feed for sheep.

3.3.2 Pot ale syrup

The DM content of PAS can vary considerably (300-500 g kg^{-1}), but when evaporated too much the product becomes viscous and difficult to handle. Age and acidity (pH typically 3.8) of the PAS can also affect its viscosity, though a thick syrup can have water added to improve the flow. At a DM content of 400 g kg^{-1}, the syrup normally flows satisfactorily and keeps well, though some separation of solids can occur. The syrup is very acceptable to cattle and sheep. It is a reasonably high source of energy and protein, though the latter is primarily as simpler nitrogenous compounds and is highly degradable (Black et al., 1984). PAS has a specific gravity of 1.2.

PAS has a very low calcium but very high phosphorus content (Black et al., 1984). In addition, the potassium and copper contents are high. The latter is discussed later (Section 4.3) with reference to toxicity to sheep. This product was fully evaluated by Wainman et al. (1984) both alone and as a mixture with draff, and this forms the main source of information given in Appendix 8.2. Results from Newbold and Wallace (1992) using the rumen simulation technique (RUSITEC) suggest that PAS can stimulate DM degradation in diets based on hay.

3.3.3 Draff

Draff is low in many minerals and trace elements, but has a satisfactory phosphorus content. It has a fairly high fat content (80-90 g kg^{-1} DM, Black et al., 1984), largely in the form of unsaturated fatty acids. Several studies have been undertaken to look at the use of draff as the sole feed for cattle and sheep (Miller et al., 1970). An awareness of the removal of certain nutrients during processing, prompted supplementation with calcium (lactate and carbonate) in particular, which resulted in increased DM intake and digestibility with sheep but not in cattle. The calcium supplementation was considered important in reducing the free fatty acids present by forming calcium soaps and so enhancing fibre digestibility. Some doubt remains regarding the benefit in terms of energy utilisation between the presence of high energy fatty acids and possible increased methane energy losses following their saponification. However, El Hag and Miller (1972) identified that the calcium soaps could improve digestibility, particularly where C18 unsaturated fatty acids were present. Draff is high in oleic and linoleic fatty acids.

Recent studies in vitro and in sacco (Offer and Offer, 1992a) have shown that calcium hydroxide can also enhance the nutritive value of draff by the formation of soaps thus enhancing the availability of the carbohydrate fraction. Further studies in vivo (Offer and Offer, 1992b) showed benefits from the use of calcium hydroxide in lamb liveweight gain arising from improved diet digestibility and increased feed intake.

It has also been shown that supplementation of distillery by-products with calcium decreases the risk of copper toxicity by decreasing the copper uptake from the intestinal tract. Wainman and Dewey (1982) fed draff and draff plus PAS to adult wether sheep. Copper toxicity was not a problem during this study of 56 days, despite dietary copper concentrations of between 17 and 30 mg kg^{-1} DM. Metabolisable energy concentrations of 10.8 and 12.5 MJ kg^{-1} DM were measured for the draff and draff plus PAS respectively. As with the DDG, lower methane energy losses were recorded than the Blaxter and Clapperton (1965) equation suggested. When metabolisable energy estimates from the work of Miller et al. (1970) were corrected for the lower methane losses, the value obtained for draff was similiar to that of Wainman and Dewey (1982).

3.4 Starch/glucose manufacturing

3.4.1 Glucose filtrate

This product is claimed by Nutrition Trading (International) Ltd. (1990) to have a use in ruminant rations directly or in aiding the ensilage of forage. It is claimed to contain 650 g kg^{-1} of DM, 50 g kg^{-1} of protein and have a metabolisable energy content of 12 MJ kg^{-1} DM.

3.4.2 Barley fibre

This product, obtained from starch-ethanol production, is essentially a source of digestible fibre. The product has been studied by Huhtanen (1992). The analysis of the barley fibre is given in Table 4.

Table 4. Chemical analysis of barley fibre (after Huhtanen, 1992).

Determination	Mean value (g kg^{-1} DM or as stated)
Crude protein	136
Ether extract	87
Crude fibre	167
Neutral detergent fibre	710
Acid detergent fibre	207
Acid detergent lignin	40
Gross energy (MJ kg^{-1} DM)	19.4

Huhtanen (1992) studied the replacement of barley (3.25 kg) with barley fibre, with or without wet distillers' solubles as a protein source. Decreased digestibility of diet components was seen, with changes in the rumen fermentation. Microbial protein synthesis was increased with the substitution of barley fibre, but the supply of additional wet distillers' solubles did not change the flow of non-ammonia nitrogen to the duodenum. Animals fed the barley fibre diets were found to have much lower numbers of protozoa in the rumen than with barley. The responses may reflect the higher fat content of the barley fibre.

3.5 Conclusions

In summary, there is considerable variability in the chemical composition and

nutritive value of cereal by-products. They are generally high in fibre but vary in the proportion of lignin, which will influence digestibility. Further, the digestibility may also be dependent on the composition of the basal diet (Boucqué & Fiems, 1988). For most by-products there is little information on protein quality in terms of rumen degradability and for DDG in particular there are doubts about the validity of the currently available techniques for estimating protein quality.

4.0 BY-PRODUCTS IN DIETS

For the use of by-products on farms, it is desirable that there is a regular supply, unless it is possible to ensile (e.g. brewers' grains). Additionally, they should remain reasonably consistent in composition between deliveries, and must keep well. These criteria will also be important for the compound feed manufacturer. The extent to which fresh as opposed to dried brewers' grains are available, depends largely on the costs of drying. This will also apply to the distillery by-products.

The relative economic value of any cereal by-product will be judged on its nutritive value compared with some of the traditional feedstuffs (e.g. cereal grains, soyabean meal) making allowance for any other attributes. Ideally, the assessment of the relative economic value of any alternative feed should be made on a least cost basis for the whole diet.

4.1 Milk production

The amount of information from research on the use of many of the cereal by-products is very limited. It is also difficult to differentiate between the amounts of by-products which are produced in the UK and those imported. Table 5 gives the cereal by-product content of the two main types of dairy compound feeds produced in the UK between 1988 and 1991 (Anon, 1991b).

4.1.1 Wheat offals for milk production

As indicated in Table 5, wheat offals are the main cereal by-product used in compound feeds. When the offals constitute a fine residue with a higher endosperm content, there is the possibility of acidosis arising if excessive quantities are fed. However, the starch content of offals is typically considerably lower than that of wheat and other cereal grains. Sloan et al.

(1988) have shown that when large quantities of compound feed, high in digestible fibre sources are fed, the typical depression of milk fat content

Table 5. Cereal by-product content (%) of two dairy compound feeds (average values for Jan-June and July-Dec) (after Anon, 1991b).

Cereal by-product	1988	1989	1990	1991
Standard dairy compound feed:				
Wheat offals	17.5	14.5	9.5	10.5
Biscuit/confectionery	3.0	2.5	2.5	2.5
Dried brewers' grains	5.5	4.0	1.5	2.0
Total cereal by-products	38.5	39.5	33.5	35.5
Summer grazing compound feed:				
Wheat offals	15.5	20.0	16.5	10.0
Dried brewers' grains	6.5	2.5	2.0	3.0
Others *	3.5	5.5	2.5	1.0
Total cereal by-products	40.5	48.5	43.0	42.5

*excluding rice bran, maize gluten feed and nutritionally improved straw.

with increasing amounts of compound feed can be alleviated. Where grain screenings are used, their inclusion will depend on quality; with reasonably clean screenings they may replace up to 50% of the cereal component of a diet.

4.1.2 Brewers' grains and draff for milk production

Traditionally, brewers' grains and draff have been used as forage replacers when silage or hay have been in short supply. As forage replacers, their use has been restricted due to their low fibre content, which can lead to digestive upsets and reduced milk fat content. The mixing of these by-products with 15% straw and 15% molassed sugar beet feed has been found to overcome some of these problems (Offer, 1990).

Traditionally, brewers' grains have a reputation for stimulating milk production (MAFF, 1983). This may be because they are very palatable and act as a succulent, particularly in dry diets, or possibly because their high protein content stimulates intake in slightly protein deficient diets. In addition to apparently stimulating milk yield, milk fat content may be increased. Typical amounts fed are 5-10 kg per cow d^{-1}, although up to 20 kg per cow d^{-1} may be satisfactory.

Draff and brewers' grains have also for many years been fed as a partial replacement for compound feed. Hyslop and Roberts (1988) looked at the extent to which mineralized draff could replace a proprietary compound feed when fed conventionally in two feeds per day. They reported that up to 15% of the total DM intake was successfully fed in this manner without affecting milk production. The maximum intake of draff that was achieved was 25% of the total DM intake, possibly due to the low DM content of the grass silage and the overall physical bulk of the total diet. Hyslop and Roberts (1989) were able to increase the use of mineralized draff in rations by feeding complete diets. They showed that up to 30% of the dietary DM (5.7 kg) as draff could be fed thus replacing a barley/soyabean meal mixture. The only difference in production was that the milk fat was of higher unsaturated fatty acid content on the diets containing draff. At higher levels of draff inclusion there was a reduction in DM intake, caused possibly by a lowered diet digestibility or the higher intake of oil.

Both feeds can be included usefully with other forages/feeds to form a buffer feed. Sodium hydroxide treated straw plus brewers' grains (1:1 DM basis) offered for 1h daily, increased milk yields and reduced the grazing requirement of dairy cows (Leaver and Campling, 1990). Brewers' grains have also been found to be of benefit when offered in addition to good quality grass silage to cows at grass (Aston et al., 1987).

Draff plus molassed sugar beet feed (Grainbeet) has been fed to cows and beef bulls (McKendrick and Roberts, 1991). When replacing up to 5kg DM of compound feed, milk yield was unchanged, but milk fat content was decreased by 4.1 g kg^{-1}.

4.1.3 Distillers' dark grains for milk production

McKendrick and Hyslop (1992) showed that replacement or partial replacement

of 7kg of standard dairy compound feed with either maize, barley or wheat DDG, fed with grass silage ad libitum, resulted in similiar milk yields (Table 6). In comparison with the 7kg of compound feed, milk fat concentration was reduced with all DDG supplements but in particular with DDG from maize. The proportion of long chain fatty acids in the milk increased on all DDG treatments and milk protein concentration was significantly higher with the wheat and barley DDG than with the compound feed. Although McKendrick and Hyslop (1992) concluded that whilst up to 7kg per cow d^{-1} was satisfactory for barley or wheat DDG, this level of maize DDG was undesirable. Inclusion rate of DDG from maize should probably be judged on the oil content of the feed.

Table 6. Milk production when dark distillers' grains (DDG) replaced compound feed (after McKendrick and Hyslop, 1992).

		DDG produced from:		
	Compound feed	Barley	Wheat	Maize
Concentrate DMI (kg d^{-1})	5.9	6.0	6.1	6.1
Milk yield (kg d^{-1})	21.2	21.7	21.7	20.2
Milk fat (g kg^{-1})	39.8	35.9	37.9	31.3
Milk protein (g kg^{-1})	31.7	32.5	32.3	30.5

Pellet quality can be very variable with DDG, which is a further limitation to the practical use of this product.

4.1.4 Pot ale syrup for milk production

Although used for dairy cows, there is generally less place for PAS in dairy diets based on grass silage due to its high protein degradability, and hence a risk of excess supply of non-protein nitrogen in the rumen (NOSCA, 1982).

4.1.5 Malt culms and barley fibre for milk production

The bitter flavour of malt culms together with the possible swelling of the

product will limit its use in diets. In addition, it has been suggested (Black et al., 1984) that the bitter taste can pass through to the milk.

There has been much interest in the use of digestible fibre supplements to increase the utilisation of the nitrogen in silage for microbial protein synthesis. Beneficial effects on milk and milk protein yield were achieved (Ala-Seppala et al., 1988) when barley fibre replaced barley in grass silage diets, despite a reduced energy supply.

Diets containing barley fibre produced lower acetate plus butyrate:propionate ratios in the rumen fluid, together with a lower milk fat content (Ala-Seppala et al., 1988). This is contrary to that typically expected, and may reflect the higher fat content of the barley fibre.

4.2 Growing/finishing cattle

Brewers' grains or draff are commonly fed up to 15 kg per animal d^{-1}. Lewis and Lowman (1989) fed diets of only ensiled brewers' grains or ensiled draff plus minerals to continental cross cattle (approximately 400kg live weight) on straw bedding. With the brewers' grains, intake and performance were disappointing initially, but improved with additional mineral supplementation (16.2 g brewers' grains DM kg^{-1} live weight and 0.85 kg d^{-1} liveweight gain respectively for the latter period). An interesting finding was the importance of adequate supplementation with magnesium. A lack of magnesium reduced DM intake, possibly due to its similar action to calcium on free fatty acids (Offer and Offer, 1992a). When the draff was fed to a second group of cattle, intake and performance was good (20.2g draff DM kg^{-1} liveweight and 0.88 kg d^{-1} liveweight gain). No benefit was seen from additional barley or sugar beet feed supplements, though the period of supplementation was short. In both cases, satisfactory carcasses were obtained.

Risk et al. (1986) noted that with cattle on maize based diets, daily liveweight gains decreased when 25 or 40% of the diet DM comprised wet draff or brewers' grains. These workers concluded that brewers' grains and draff could form effective energy and protein sources only when used as part of the ration. Dried brewers' grains have been shown to satisfactorily replace soyabean meal in cereal-based rations fed to young beef cattle (Oster et al., 1977). Liveweight gains were similiar, but where high inclusion rates of

brewers' grains were used (36% of the compound feed), feed conversion efficiency declined, possibly due to a lower energy intake. In addition, the inclusion of dried brewers' dried grains appeared to reduce the incidence of rumen keratosis.

PAS is useful in diets based on straw and low quality forage, acting as both a protein and energy supplement. By supplying additional protein, PAS can increase the digestibility of the diet, but not necessarily increase the intake of forage. The use of PAS in the diets of growing animals has been reviewed by Kay (1985). He suggested that about 0.75 kg of PAS DM would support similar liveweight gains to 1.0 kg of barley DM when PAS was fed at up to 0.82 kg DM per animal d^{-1}. Large amounts of PAS can decrease forage digestibility (Black et al., 1984), and it is suggested that the PAS should not exceed half the DM intake. NOSCA (1982) claim that PAS may be more efficiently utilised when fed with a small inclusion of cereal in the diet. If not added to the forage or included in a complete diet PAS may be fed via ball or wheel feeders or in open troughs (with logs added to prevent over consumption).

There is potential for the use of PAS mixed with straw as a buffer feed. The syrup has been used with limited success for adding to hay and straw at the time of baling. It has not proved successful as a silage additive due to the large amounts required (Black et al., 1984).

The maximum inclusion rates for cereal by-products in the diets of growing and finishing cattle have been proposed by various sources. The figures given in Table 7 are from MAFF (1985) and also include suggestions relative to dairy cows and sheep.

Table 7. Suggested maximum dietary inclusion rates (g kg^{-1} total diet DM) of cereal by-products (after MAFF, 1985).

Class of animal	Middlings	Grain screenings	Dried brewers' grains	Distillers' dark grains
Cattle:				
Calves	100	100	100	100
Growing cattle	200	200	200	200
Cows - beef/dairy	250	200	200	200
Sheep:				
Lambs	150	100	100	100
Ewes	250	150	100	100

4.3 Sheep

The largest amounts of the cereal by-products, particularly those from brewing and distilling, are fed to cattle but they can also be very acceptable to sheep.

As already indicated, PAS and DDG can have high copper contents and should therefore be fed to sheep with caution (Black et al., 1984). Although the availability of copper from distillery syrups may be low, toxicity can arise and indeed in the evaluation of distillers' grains at the Rowett Research Institute, cases of copper toxicity occurred in the sheep used. Susceptibility to death from copper toxicity varies between individual sheep and cannot be reliably forecast through the amount ingested or via blood analysis (Wainman et al., 1984). NOSCA (1982) suggested that PAS should not be fed to sheep at more than 0.7kg per animal d^{-1}. There remains, however, the possibility that the high copper content may be of benefit in copper deficient areas.

Malt culms have been used with some success in rations for ewes where bulk in the ration has been felt to be important for pregnant and lactating ewes (Black et al., 1984).

4.4 Storage and handling of by-products on the farm

Storage conditions of wet brewery and distillery by-products can affect their nutritive value, and hence a short discussion is included.

The demand by farmers for brewers' grains and draff is less consistent than is their production. It is necessary, therefore, to consider the storage of these by-products on the farm. In addition, there may be price advantages to purchase during the summer months.

The feeding of fresh or ensiled brewers' grains or draff is essentially the same once differences in the DM content are taken into account. Ensilage should be within a few days of delivery if mould development is to be avoided and DM losses are to be minimised.

Space requirement for storage of draff is 1.0-1.2m^3 t^{-1} ensiled depending whether it is compacted or not or mixed with sugar beet pulp (Hyslop and Offer, 1989). Alternatives to this process include ensiling beneath grass or maize silage, or mixing it in a silo with wet maize gluten feed. Whether brewers' grains or draff are stored alone, or in combination with other feeds, there is the potential problem of DM losses, in particular as effluent.

In order to overcome the loss of the most soluble and digestible components of draff, different methods of ensiling including the inclusion of molassed sugar beet shreds have been examined (Hyslop and Offer, 1989). Careful ensiling reduced DM losses from 268 to 130 g kg^{-1}, largely due to less 'visible' wastage. The addition of the molassed beet shreds (158 kg t^{-1} draff) reduced DM losses to 62 g kg^{-1}, largely due to decreased 'invisible' losses, and the prevention of effluent production. Although the addition of molassed sugar beet shreds reduced the silo capacity, DM intake and liveweight gain in young Friesian steers was increased significantly (Hyslop et al., 1989). The addition of sodium chloride to draff at ensilage has been attempted with the aim of reducing DM losses (El Hag and Miller, 1972). No benefit was observed in DM losses or digestibility, but magnesium retention appeared to decrease which could be of importance (Miller et al., 1970).

Supergrains are more difficult to store, with emphasis required on sheeting and sealing. Supergrains should be fed within 24 h of exposing to air if moulding is to be avoided (Offer, 1990).

5.0. BY-PRODUCTS IN COMPOUND FEEDS

The use of cereal by-products originating from UK grain by members of UKASTA, has historically been high, although the availability to compounders of distillery by-products is reducing due to reduced whisky production and increasing sales of by-products directly to farms (UKASTA, Pers. Comm.).

The amount of distillery by-products used is limited by the variability of the product source. Simply separating the products into the three major parent cereal species is unsuitable due to different production conditions at different distilleries. For example, Strathclyde and Vitaferm products are both wheat-based, but differ markedly in chemical analysis and feeding value (UKASTA, Pers. Comm.).

The high oil content of distillery and brewery by-products, and the unsaturated fatty acid profile, limit their use in compound feeds, especially for dairy cows, due to the potential negative effects on fibre digestion within the rumen. The high copper concentrations in some by-products precludes their use in compound feeds for sheep.

PAS has been mixed with molasses and used in liquid feed blends. Appendix 8.4 shows the typical maximum inclusion rates in compound feeds for DDG from different sources together with their chemical composition (UKASTA, Pers. Comm.) The values shown are means, around which there is considerable variation, particularly in the maximum inclusion rates used.

6.0 RECOMMENDATIONS FOR RESEARCH

From being regarded as waste products, cereal by-products now need to be utilised well for economic and environmental reasons. Many of the by-products are well suited to feeding to ruminants. However, a better appreciation is required of their nutritional values and limitations in diets. The following research requirements have been identified. They have been categorised as having very high, high and moderately high priority.

1. **Very high priority**

i. Develop rapid laboratory procedures for estimating the energy value of different cereal by-products.

ii. Establish protein degradability in animals, including a study into the validity of current techniques for estimating nitrogen degradability and unavailable nitrogen in dried distillery and brewery by-products.

iii. Develop laboratory procedures to predict more accurately protein quality of different by-products.

2. **High priority**

i. For brewery and distillery by-products containing high concentrations of unsaturated oils, further elucidate the relationship between divalent cation supplementation, rumen function and methanogenesis.

ii. Study the influence of the unsaturated oil content of distillery and brewery by-products on milk composition in dairy cows and carcass quality and fat composition in cattle and sheep.

iii. Study the effect of the lactic acid present in wet brewery and distillery products on the rumen environment and any interaction with the amounts and type of other feeds in the diet, particularly grass silage.

3. **Moderately high priority**

i. Further study the use of cereal by-products as silage absorbents/inoculants.

ii. On completion of the very high and high priorities, evaluate these by-products in animal production systems.

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8.0 APPENDICES

Appendix 8.1. Composition and nutritive value of milling offals and wheat grain (g kg^{-1} DM unless indicated) (after MAFF, 1990).

Composition and nutritive value	Wheat feeds		Wheat offals		Wheat bran		Wheat grain	
	Mean	SD[1]	Mean	SD	Mean	SD	Mean	SD
Chemical composition:								
Oven dry matter	890	18.0	878	6.3	892	11.3	857	21.2
Crude protein (CP)	179	12.8	185	17.4	174	15.0	128	16.5
Crude fibre (CF)	81	14.3	70	19.9	104	12.9	21	4.1
Oil	51	3.2			52	3.2	21	2.5
Ash	51	1.4	51	11.6	66	5.4	17	2.2
Gross energy (GE, MJ kg^{-1} DM)	19.1	0.19	19.1	0.15	18.9	0.13	18.4	0.23
NDF[2]	364	53.6	354	81.7	475	54.7	123	21.1
ADF[3]	111	18.2	104	26.9	137	20.5	30	4.3
Lignin	35	8.6	36	6.1	40	6.1	11	2.3
Starch	277	75.2	329	108.4	196	49.2	675	33.1
Sugars	57	6.1	-	-	64	7.5	27	9.5
NCD[4]	748	15.2	-	-	685	38.7	928	6.3
Calcium	1.1	0.14	1.0	0.11	1.1	0.18	0.55	0.21
Phosphorus	10.5	2.0	11.9	1.2	12.6	3.0	3.3	0.42
Magnesium	5.2	2.6	8.7	1.8	6.2	2.7	1.1	0.13
Sodium	0.14	0.06	0.14	-	0.12	0.03	0.12	0.06
Nutritive value:								
Metabolisable energy (MJ kg^{-1} DM)	11.9	1.0	11.9	0.95	10.8	0.65	13.7	0.62
OM[5] digestibility	0.77	0.04	0.77	0.04	0.75	0.04	0.9	0.02
GE digestibility	0.75	0.05	0.75	0.04	0.71	0.04	0.88	0.03
CF digestibility	0.48	0.1	-	-	-	-	0.67	0.21
NDF digestibility	0.54	0.03	-	-	-	-	0.6	0.12
CP digestibility	0.75	0.01	-	-	-	-	0.77	0.05

1, Standard deviation for the population; 2, Neutral detergent fibre; 3, Acid detergent fibre; 4, Neutral detergent-cellulase digestible organic matter.
5, Organic matter

Appendix 8.2. Composition and nutritive value of fresh brewers' grains and draff (g kg^{-1} DM unless indicated) (after MAFF, 1990).

Composition and nutritive value	Fresh brewers grains		Draff	
	Mean	SD[1]	Mean	SD
Chemical composition:				
Oven dry matter	250	31.3	248	7.1
Toluene dry matter	261	34.4	255	-
Crude protein (CP)	218	34.2	211	5.0
Crude fibre (CF)	171	16.9	199	12.0
Oil	55	13.7	-	-
Ash	38	6.0	34	1.4
Gross energy (kg^{-1} DM) (GE, MJ kg^{-1} DM)	21.3	0.35	21.5	0.14
NDF[2]	618	63.9	673	23.3
ADF[3]	264	44.5	294	42.4
Lignin	86	36.5	63	7.1
Starch	38	24.4	18	5.0
NCD[4]	591	35.8	-	-
Calcium	3.5	1.4	1.5	-
Phosphorus	5.1	1.0	3.8	-
Magnesium	1.7	0.36	1.8	-
Sodium	0.26	0.3	0.1	-
Nutritive value:				
Metabolisable energy (MJ kg^{-1} DM)	11.5	0.65	10.2	0.92
OM[5] digestibility	0.60	0.03	0.52	0.03
GE digestibility	0.61	0.03	0.54	0.03
CP digestibility	0.77	0.03	0.74	0.01

1, Standard deviation for the population; 2, Neutral detergent fibre; 3, Acid detergent fibre; 4, Neutral detergent-cellulase digestible organic matter; 5, Organic matter.

Appendix 8.3. Composition and nutritive value of distillery by-products (all g kg^{-1} DM unless indicated) (after MAFF, 1990).

	Distillers dark grains - barley		Distillers dark grains - wheat		Malt culms		Pot ale syrup
	Mean	SD[1]	Mean	SD	Mean	SD	Mean
Chemical composition:							
Oven dry matter	907	20.9	890	32.8	915	28.9	483
Crude protein (CP)	275	13.1	302	25.5	283	26.4	374
Crude fibre (CF)	121	12.8	89	12.8	137	12.6	2
Oil	85	7.8	69	17.4	26	4.2	-
Ash	60	4.2	52	10.3	65	2.4	95
Gross energy (GE, MJ kg^{-1} DM)	21.3	0.26	21.5	0.65	18.7	0.35	20.0
NDF[2]	420	21.9	335	91.2	463	34.9	6
ADF[3]	175	13.4	193	58.0	163	23.3	-
Lignin	32	2.8	85	50.2	11	3.5	15
Starch	26	8.4	45	19.8	63	36.0	13
Sugars	39	18.0	63	8.1	107	47.9	-
NCD[4]	687	19.8	822	42.6	381	17.6	-
Calcium	1.7	0.32	1.8	0.62	2.7	1.00	1.9
Phosphorus	9.6	0.80	8.8	1.10	7.4	0.90	20.1
Magnesium	3.3	0.34	2.8	0.44	2.0	0.34	6.4
Sodium	1.2	1.20	3.1	3.90	0.42	0.08	0.9
Nutritive value:							
Metabolisable energy (MJ kg^{-1} DM)	12.2	0.18	12.4	0.29	-	-	15.4
OM[5] digestibility	0.65	-	0.74	0.04	-	-	0.89
GE digestibility	0.67	-	0.73	0.03	-	-	0.89
CF digestibility	-	-	0.58	0.02	-	-	0.78
NDF digestibility	-	-	0.59	0.12	-	-	-
Nitrogen degradability[6] 'a' (%)	-	-	84.0	8.9	-	-	-
'b' (%)	-	-	11.7	7.0	-	-	-
'c' (h^{-1})	-	-	0.17	0.10	-	-	-

1, Standard deviation for the population; 2, Neutral detergent fibre; 3, Acid detergent fibre; 4, Neutral detergent-cellulase digestible organic matter.
5, Organic matter; 6, 'a' = immediately soluble nitrogen, 'b' = insoluble but potentially degradable fraction, 'c' = rate of degradation of 'b'.

Appendix 8.4. Inclusion rate in compound feeds and chemical composition of wheat and barley based distillers' dark grains (DDG) (after UKASTA Pers. Comm.).

By-product and source	Maximum inclusion in compound feeds (g kg^{-1})			Chemical composition (g kg^{-1})				
	Dairy	Beef	Sheep	Ether extract	AH[1] ether extract	Crude protein	Crude fibre	Ash
Wheat DDG								
Vitaferm	300	320	200	70	86	350	132	31
Straithclyde	300	250	250	43	70	284	75	41
Invergordon	300	300	250	60	75	310	100	50
Long John	300	300	250	44	60	283	74	37
Port Dundas/Cambus	300	300	0	45	67	300	76	36
Barley DDG								
Rothes	270	320	175	60	71	244	111	47
Glenlossie)	300	300	300[2]	77	81	240	118	51
Aultmore)								

1, Acid hydrolysis.

2, after checking copper levels.

SECTION 3

CEREAL STRAWS

by

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1.0 INTRODUCTION

Straw comprises the stem with or without leaves of members of the Gramineae family, from which the seed head has been removed. The name straw is usually given to the six major slender-stemmed cereals namely, wheat, barley, oats, triticale, rye and rice. Whilst from the botanical viewpoint there is no clear distinction between this group and many other members of the Gramineae family, this review will concentrate on the nutritional aspects of straws from the main cereal crops grown in the United Kingdom. Staniforth (1992) has reviewed the use of straw as a feed for non-ruminants together with other non-nutritional uses. Some of the non-nutritional uses examined included the use of straw for matting and mulch to prevent soil erosion, controlling weeds in forests and cardboard manufacture.

1.1 Quantities of straw available

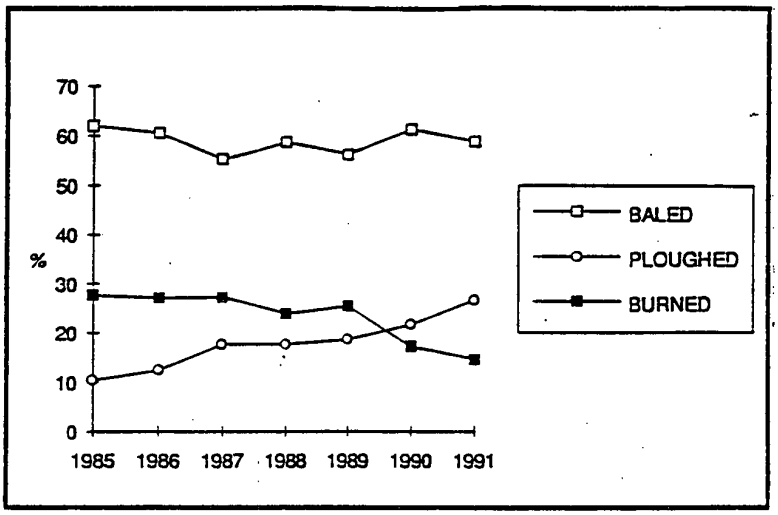
The quantity of cereal straw potentially available for feeding in the UK is large. Estimates by MAFF (1991) of the areas of the different cereals grown in 1991 in England and Wales were 1871, 776, 248 and 74 x 10^3 ha for wheat, winter barley, spring barley and oats respectively. These areas, together with the straw yields per hectare given by Larkin (1984), have been used to calculate estimates of the weight of straw available from England and Wales in 1991 (Table 1). Table 1 also gives estimates of quantities of straw baled and removed, straw ploughed in or cultivated and straw burnt in the field based on estimates by MAFF (1991).

Table 1. Estimates of straw available in England and Wales in 1991.

Cereal	Quantity of straw (x10^6t)			
	Total	Baled	Ploughed in	Burned
Wheat	8.90	3.80	3.20	1.90
Winter barley	3.10	2.60	0.34	0.13
Spring barley	0.61	0.52	0.07	0.02
Oats	0.22	0.19	0.02	0.01
Total	12.80	7.10	3.60	2.10

Overall, only about 57% of straw produced was baled and removed from the field, although this figure was approximately 85% for all cereals other than wheat. MAFF (1991) have estimated the trends in straw disposal and Figure 1 shows these for all cereals covering the years 1985-1991. The decline in straw burning is clear, although this appears to be largely compensated for by an increase in straw being incorporated into the soil.

Figure 1. Trends in straw disposal (after MAFF, 1991).



In simple metabolisable energy (ME) equivalents, the total straw available for feeding in England and Wales (7.1×10^6t) is approximately equivalent to 3.6×10^6t of compound feed. In practice, much of the baled straw is not fed, with considerable amounts being used for bedding.

2.0. STRUCTURE AND COMPOSITION OF STRAW

Straw consists mainly of highly lignified cell wall material with very low concentrations of proteins and storage carbohydrates. Straw is, however, not a homogenous material and consists of varying amounts of different plant parts.

2.1. Straw fractions

A review of the various anatomical fractions of straws has been given by Theander and Åman (1984), and Juniper (1991) has compared the structure of straw to engineered structures. The yields of the different anatomical fractions of straw have been reported by several workers and some of these

data are presented in Table 2. Table 2 indicates some variation between observations within the same cereal species. Shand et al. (1988) have also shown variation between varieties of wheat harvested from experimental plots.

Table 2. Yields of different botanical fractions of cereal straws.

Cereal	Yield of fraction (g kg^{-1} DM)			Reference
	Internode	Node	Leaf	
Barley	585	66	349	Åman and Nordkvist (1983)
Spring wheat	576	44	380	Müller (1960)
Winter wheat	540	48	410	Müller (1960)
Winter wheat	727	68	205	Åman and Nordkvist (1983)
Oats	528	36	436	Müller (1960)

Some of the data from Shand et al. (1988) are summarised in Table 3. Of particular note is the range in the proportion of leaves in wheat varieties (278-366 g kg^{-1}). Goto et al. (1991) have presented similar data for varieties of barley straw, these are also shown in Table 3.

Table 3. Proportions of botanical fractions from different varieties of wheat and barley straws (after Shand et al., 1988; Goto et al., 1991).

Variety	Botanical fraction (g kg^{-1} fresh weight)			
	Leaf blade + sheath	Internodes	Nodes	Chaff
Wheat straws:				
Brimstone	278	493	76	153
Stetson	304	483	51	162
Longbow	331	468	54	147
Brock	366	491	60	83
Barley straws:				
Golden Promise	324		676	
Klaxon	400		600	
Doublet	470		526	

Whilst there can be considerable variability both between and within species, the data available suggest that barley and oat straws are likely to have greater proportions of leaf than wheat straw. The proportion of leaf is of considerable importance since the digestibilities of the leaves in wheat, barley and oat straws are considerably higher than stems (Shand et al., 1988; see also Section 4.3). It is worth recording that various other factors such as stubble length can influence the proportion of leaf.

2.2. Chemical composition

A comprehensive analysis of the major fractions of 51 barley, 62 wheat and 5 oat straws harvested in England and Wales was reported by Givens et al. (1989). Some of these data are reproduced in Table 4. Cell walls measured as neutral detergent fibre (NDF) occupied by far the largest fraction and the values in Table 4 are similar to those reported earlier by Jackson (1977) and Pearce et al. (1979).

Apart from the structural carbohydrates, lignin is a major component of straw. Lignin encrusts the cell walls and develops ester covalent bonds with hemicelluloses. This seriously limits the degradation of the cell walls in the rumen. In this regard, it is noteworthy that the concentration of lignin in the straw does not seem to be closely related to the availability of the cell wall to rumen microorganisms (Chesson, 1988). Degradation of the cell walls is much more determined by the physico-chemical associations between the components of the cell wall (Chesson, 1988; Chesson and Murison, 1989). In particular, lignin prevents close contact between the cell walls and the rumen microorganisms. For further details of the lignin-cell wall complexes and how these influence the degradation by rumen microbes, the reader is referred to the extensive reviews of Chesson (1988) and Grenet and Besle (1991).

Because of the rather limited biological relevance of chemical analysis of straws, substantial developments have taken place in physical techniques for studying cell wall structures. These have included scanning electron microscopy (Akin et al., 1975), X-ray auto-fluorescence (Willemse, 1981) and more recently nuclear magnetic resonance (Himmelsbach, 1989) and multiple internal reflectance infrared spectroscopy (Russell et al., 1988). Details and recent findings of some of these methods have been presented by Chesson and Ørskov (1989).

Table 4. Chemical composition of cereal straws (g kg^{-1}DM or as stated) (after Givens et al., 1989)

Component	Wheat straws	Barley straws	Oat straws
Dry matter (g kg^{-1} fresh)	868	865	832
Crude protein	40	43	40
Total ash	72	58	67
Neutral detergent fibre (NDF)	806	809	732
Hemicellulose	314	296	243
Cellulose	400	413	420
Lignin	99	98	93
Water soluble carbohydrates	12	17	14
Gross energy (MJ kg^{-1}DM)	18.1	18.4	18.1

3.0 DIGESTION AND RUMEN FERMENTATION

3.1 Rumen digestion

The majority of feed ingested by herbivorous mammals is high in structural carbohydrates (principal components of the cell walls). These carbohydrates are mainly cellulose and hemicellulose. No herbivorous mammals have the ability to digest these polysaccharides, but many microorganisms synthesise enzyme complexes capable of degrading them. Ruminants have evolved a digestive system whereby they can utilise cell wall components by means of a symbiotic association with microorganisms in the rumen capable of digesting these polysaccharides.

The rumen can be likened to a highly efficient semi-continuous fermentation apparatus, but differs from the man-made fermentation equipment in several ways. The inner epithelial wall of the rumen is semi-permeable and selectively transports small molecules to and from the animal's bloodstream. Neural responses to specific stimuli exist, such as activation of physiological mechanisms for eructation and activation of contractions to mix and move rumen contents. The biological features of the rumen provide mechanisms for fermentation of solid substrates, product removal, maintenance

of pH and disposal of fermentation gases. Many aspects of rumen ecology and physiology have been reviewed by Czerkawski (1986).

The rumen is a warm (39°C) anaerobic, chemically reducing (oxidation-reduction potential about -350mv) environment rich in organic matter. The pH of the rumen contents is approximately 6.5. This is held relatively constant by the buffering action of the large amount of secreted saliva, which is high in sodium and potassium bicarbonate and urea, by absorption through the rumen wall into the bloodstream of volatile fatty acids (VFA) and by ammonia (NH_3) produced during fermentation.

Temperature, oxidation-reduction potential and pH are constraints on the types of microorganisms that can exist in the rumen. Despite these constraints, the rumen contains a very varied, complex and dense population of microorganisms. These may be split into three main groups : bacteria (1×10^{10} to 1×10^{11} ml^{-1}), protozoa (ciliates 1×10^{4} to 1×10^{6} ml^{-1}; flagellates 1×10^{3} to 1×10^{5} ml^{-1}) and fungi.

Cereal straws differ in two important respects from the vast majority of other plant materials offered as feed to ruminant animals: (1) The carbohydrates present in straw are found only in the structural form, with the virtual absence of water soluble carbohydrates and starch. (2) Straw is not the primary product and its harvest is dictated by the maturation of the grain. As a consequence, the process of lignification which accompanies the maturation of all plants is considerably more advanced in straw than in other forage plants. Virtually all the cells within cereal straws are dead, devoid of the cell contents which add to the nutritional value of other forage plants, and are uniformly and extensively lignified. Thus, the digestion of straw by the rumen microorganisms is virtually synonymous with the digestion of straw cell walls (Chesson and Ørskov, 1989).

Rumen fermentation of ligno-cellulosic (fibre-rich) feeds occurs in a complex system that is influenced by many factors. Some of the more important constraints limiting fibre digestion are as follows:

1. The physical and chemical nature of the fibre.
2. The rate of ruminal digestion.
3. The nature and population densities of the predominant species of fibre digesting microorganisms as affected by the prevailing ruminal conditions.

The physical and chemical nature of forages can present a barrier to their complete digestion in the rumen. The association of lignin with polysaccharide constituents of cell walls limits microbial digestion with lignin protecting about 1.4 times its own mass of cell wall carbohydrates (Van Soest, 1981).

3.2. Degradation of the cell walls by microorganisms

Microorganisms in the liquid environment of the rumen, in order to find the nutrients they require and to avoid being carried out of the rumen by the digestive flow, need to adhere to particulate matter. The microorganisms that use cell wall polysaccharides as their main energy source exist in close relation with the food particles that enter the rumen and are thus able to remain in the rumen as long as do the latter. The ability of the cellulolytic microorganisms to become attached to plant fibre is important and has been well documented. Early studies of ruminal contents by light microscopy showed bacteria within the lacunae (i.e. zones of digestion) suggesting that adherence might be important in plant fibre degradation (Baker and Martin, 1938). Apart from these general descriptive studies, little is known of the mechanisms for attachment. The use of electron microscopy has demonstrated that coccoid bacteria are the most common adherents to plant fibre and that cell wall type or structure has an important influence on digestion rate (Akin, 1980; Akin et al., 1974).

3.2.1. Adhesion

Bacteria, protozoa and fungi colonise nearly all the plant particles that enter the rumen, with the exception of intact plant matter, i.e. protected by the epidermis. The main colonisation routes are lesions in the epidermis or through leaf stomata (Cheng et al., 1983/84). Demeyer (1981) reported that plant tissue particles entering the rumen are colonised by bacteria within 5 min, by protozoa within 15 min and by fungal sporangia and rhizoids within 2h.

It has been shown with several species of ruminal bacteria that non-cellulolytic or weakly cellulolytic bacteria adhere to cellulose particles to a lesser extent than the actively cellulolytic strains (Minato and Suto, 1978). The main cellulolytic bacteria species that attach to particles are Fibrobacter succinogenes (a gram-negative rod), and

Ruminococcus albus and R. flavefaciens (gram-positive cocci). The Ruminococcus species appear to be loosely associated with cell walls, while F. succinogenes exhibits a tight adhesion, moulding itself to the surface of the cell wall being digested (Forsberg et al., 1981; Cheng et al., 1983/84).

Rumen protozoa and fungi also colonise plant fragments and degrade them to differing extents (Akin, 1986). The mechanism of attachment of these organisms to plant material is little understood. Anaerobic fungal zoospores attach preferentially to the stomata and to damaged areas of particles from where soluble sugars diffuse, causing a chemotaxic response from the zoospores. Zoospores swim to acceptable sites for colonisation, encyst and invade the tissue via thallus formation and rhizoids (Bauchop, 1981). It is the lignified tissues that are preferentially colonised by the rumen fungi. It appears likely that rumen fungi can digest cellulose and hemicelluloses even when they are present in lignified cell walls (e.g. as in wheat straw). However, there is no evidence that they can digest lignin itself (Grenet and Barry, 1988).

The mechanism of attachment of different rumen microorganisms to cellulose and other complex fibrous materials may involve specific binding by cell surface-associated enzymes or possibly non-specific ionic interaction (Forsberg, 1986). Bacterial attachment has received most study and it has been shown that adhesion of R. albus was markedly decreaseed at pH below 5.0, but was unchanged between pH 5.5 and 8.0 (Morris, 1988). Soluble cellulose derivatives (carboxymethylcellulose and methylcellulose) are inhibitory toward adhesion (Rasmussen et al., 1989).

Further research should be aimed at resolving the mechanism underlying binding, since it appears to be of prime importance in the digestion of plant cell walls (Cheng et al., 1983/84).

3.2.2. Enzymes produced by the rumen microorganisms

The main cellulolytic bacteria of the rumen produce cellulases. R. albus (Strain RAM) produces a cellulase most active at pH 6.0-6.8, at a temperature of 45°C (Smith et al., 1973). The cellulases produced by R. flavefaciens have been studied by Pettipher and Latham (1979a,b). Their optimum activity is at pH 6.4 to 6.6 and at a temperature between 39 and 45°C. F. succinogenes has high hydrolytic activity against cellulose and produces

large amounts of endoglucanase and ß-glucosidase (Groleau and Forsberg, 1981) which may be intra- or extra-cellularly active. An endoglucanase was isolated by McGavin and Forsberg (1987) with an optimum pH and temperature of 7.0 and 39°C respectively. The hemicellulolytic activities of the main fibrolytic bacteria have been listed by Chesson and Forsberg (1988).

The ciliate protozoa and rumen fungi also possess cellulases and hemicellulases (Chesson and Forsberg, 1988). The activity of these enzymes is lower in the ciliate protozoa than the cellulolytic bacteria. The cellulolytic enzymes produced by rumen fungi are of a broad range, with high activity (Williams and Orpin, 1987).

Pectolytic enzymes, esterases and lyases are also produced by bacteria and protozoa, but not by anaerobic fungi (Chesson and Forsberg, 1988).

3.2.3. Microbial interactions in the rumen

The many interactions between or within rumen microbial populations was recently reviewed by Wolin and Miller (1988). Of particular importance is the synergism between cellulolytic and non-cellulolytic species. An efficient degradation of plant cell wall can be achieved only by the activities of combinations of populations: hydrolytic, fermentative and methanogenic.

The majority of non-cellulolytic bacteria in the rumen of animals fed high roughage diets are in close association with plant material and with the cellulolytic species. They hydrolyse the non-structural carbohydrates, starch and fructosans and protein and may ferment cellulose fragments, xylose, cellobiose and pentose. They may, as a result, increase cell wall degradation by disposing of products such as pentose, and alleviate catabolic repression. They also provide the cellulolytic bacteria with amino acids and growth factors (Durand, 1989).

Interspecies transfer of hydrogen to methanogens to keep a low partial pressure of hydrogen in the rumen is particularly important for the efficient metabolism of many bacterial species. Such hydrogen transfer also takes place between methanogens and populations of protozoa and fungi. Physical associations between entodiniomorphs (protozoa) and methanogens have been

observed (Demeyer, 1981). The activity of fungal enzymes is enhanced by co-culture with methanogenic bacteria (Akin, 1986).

Information of fungal-bacterial interactions and fungal-protozoal interactions is very scarce and needs to be clarified if the understanding of the role of rumen microorganisms in cell wall degradation is to be expanded (Akin and Borneman, 1990).

An optimised digestion of high straw diets relies on the right balance between the microbial populations involved. Supplementation with other types of carbohydrate, inadequate supply of certain nutrients and use of some additives can result in proliferation of organisms at the expense of cellulolytic species.

3.2.4. Limitations to cell wall degradation

Ingested cell wall polysaccharides are rarely completely degraded by the microflora in the rumen and significant amounts escape fermentation in the rumen and large intestine, being voided in the faeces. Plant tissues are made up of a heterogenous population of cells and cell walls which are degraded to differing degrees by the rumen microorganisms. The extent to which cell walls are attacked depends upon factors, both external and internal to the plant cell wall.

3.2.4.1. External factors

Much of the surface of plant particles entering the rumen may be protected by epicuticular waxes and the cuticle, both of which prevent the rumen microflora from attacking. The microorganisms are dependent on broken edges of feed particles or naturally occurring openings such as the stomata or lenticels to provide access to suitable substrates. Walls of the deeper lying cells remain protected from attack for longer periods than those cells forming the more superficial layers. Chesson et al. (1986) showed that isolated mesophyll and epidermis cell walls prepared from ryegrass leaf, when incubated in the rumen of sheep, degrade at exactly the same rate with complete digestion in 8h. However similar observations with intact ryegrass leaves showed the leaf mesophyll to be extensively digested, but the epidermis was little affected (Akin, 1988).

Even where bacteria obtain entry into the cell lumen, degradation of the cell wall has been shown to be limited by the presence of a layer lining the inner surface of the lignified cell walls. This layer may require mechanical disruption to allow digestion by adherent bacteria to occur (Engels and Brice, 1985).

3.2.4.2. Internal factors

For intact cell walls, factors other than the fine structure of the polysaccharides affect degradability. In lignified tissues like cereal straw, these factors are related to the phenolic compound content of the cell wall. Staining of the lignified tissues by histological methods confirms that the walls which are little degraded in the rumen are very lignified (Akin, 1989; Grenet and Barry, 1991), while if the plants are delignified, digestion of the walls of previously lignified tissues is improved (Chesson, 1981).

Lignified cell walls are probably not sufficiently porous to allow free diffusion of cellulolytic enzymes. As a result the microbes can attack only the surface of the cell walls. The polysaccharides accessible to the microorganisms (i.e. those not covered with lignin) are eliminated from the surface of the cell walls. Eventually a protective layer of lignin remains on the surface and prevents any further degradation (Chesson and Forsberg, 1988).

The walls of the different types of cells present in straw are of different compositions (Gordon et al., 1983) and are degraded at different rates (Chesson et al., 1986). Cereal straw cell walls are predominantly made up of the more resistant thickened secondary walls with a high hemicellulose content.

3.3. Optimisation of cell wall degradation

In the previous section, it has been established that digestion in the rumen is dependent on the activity of the microorganisms, which need energy (ATP), nitrogen (ammonia, peptides and amino acids), minerals, and a medium in which the pH is within the range 6-6.5. Poor quality roughages, such as cereal straws, have insufficient nitrogen, sugar, starch and mineral contents to

satisfy microbial needs and therefore need to be supplied to optimise cell wall degradation.

3.3.1. Supply of nitrogen

3.3.1.1. Amount of nitrogen required

Most cellulolytic bacteria require ammonia (NH_3) as the nitrogen (N) source for incorporation into cell protein. Ammonia is supplied by deamination of feed and endogenous protein amino acids or by degradation of dietary and endogenous non-protein N (NPN) such as urea. The amount of N required can be related either to the concentration of NH_3 in the rumen medium or to the potentially degradable organic matter.

The levels of NH_3-N for maximum microbial activity range from 50-280 mg N l^{-1}. This wide range is a result of different requirements for microbial growth and fermentative activities, different pathways of NH_3-N incorporation (Hespell, 1984) and type of substrate. For example, the minimum NH_3-N concentration required to maximise the degradation of barley (125 mg l^{-1}) was greater than that for degradation of maize (61 mg l^{-1}) (Odle and Schaefer, 1987). Salter and Slyter (1974) advocated a minimum value of 50mg NH_3-N l^{-1} for optimum microbial growth.

Numerous determinations of the amount of N incorporated into microbes in relation to the organic matter apparently digested in the rumen (OMDR) or the organic matter fermented (OMF) have been carried out <u>in vivo</u>, with variable results. Values for high roughage diets were reported by Demeyer and Van Nevel (1986) to be within the range 28-36 g N kg^{-1} OMDR. A proportion of microbial requirements for N can be supplied by nitrogen recycling of muco-proteins in saliva, urea through saliva and diffusion through the rumen wall and of keratinized protein in cells sloughed from the rumen wall (Egan <u>et al</u>., 1986). The levels of recycled N are extremely variable and dependent on many factors. Durand (1989) recommended a total nitrogen requirement approximating to 26g N kg^{-1} organic matter apparently digested in the total digestive tract (OMD). However, contribution of recycled N may reduce these figures by 10-40% depending on straw treatment.

3.3.1.2. Source of nitrogen

Traditionally, straw-based diets have been supplemented with urea in order to supply sufficient N for optimum microbial synthesis. Demeyer (1981) reported that the proportion of rumen microbial N which is derived from NH_3-N may be as low as 20% and varies with dietary protein content. Wallace (1991) suggested that adding extra pre-formed amino acids or indeed peptides or proteins to the diet could stimulate the mixed microbial population, in circumstances where the supply of amino acid N is low. This could be due to the fact that cellulolytic bacteria require small amounts of amino acids and peptides, as well as branched chain fatty acids which are growth factors and can be synthesised from amino acids. This could be the case with straw diets which have a low degradable protein content.

This has been supported by in vivo studies. McAllan and Smith (1983) found increased cellulose digestibility in the rumen with diets based on untreated and alkali treated barley straw when the supplement was fishmeal compared with urea. Further positive responses to protein supplementation have been observed and reported on in more detail by Hvelplund (1989). It is suggested that the combination of urea and a small proportion of slowly degraded protein to provide a steady supply of peptides and/or amino acids would favour cellulolytic activity in straw-based diets.

3.3.2. Mineral and trace element supply

The role of mineral elements in rumen microbe metabolism has been emphasised in recent reviews (Durand and Kawashima, 1980; Durand and Komisarczuk, 1988). With straw-based diets, an adequate supply of the required elements is of particular importance as mineral content and/or availability in straw can be very low (Durand, 1989).

3.3.2.1. Sulphur

The main function of sulphur (S) is to support the synthesis of sulphur-amino acids, methionine and cystine, needed for the elaboration of microbial protein. Many in vivo studies, reviewed by Komisarczuk-Bony and Durand (1991) have shown the positive effects of a S supplementation on the ruminal degradation of cell wall constituents. In vitro, Stevani and Durand (1989) showed that S supplementation significantly increased the degradation of

cellulose and hemicellulose fractions of a treated straw. These results emphasise that, for lignocellulose substrates, more S is needed to optimise the degradative processes. An adequate S supply optimises cellulose degradation by a specific stimulation of the cellulolytic bacteria (Slyter and Chalupa, 1984) and of the activity of ciliate protozoa (Spears et al., 1985). Rumen fungi have also been shown to be positively influenced by S (Akin and Windham, 1988). Durand (1989) recommended total requirements for available S to be 1.8 g kg^{-1} OMD. In straws, sulphur availability is very low and would not exceed 30%. With discontinuous feeding, slow-release S compounds such as elemental S or methionine, which minimise sulphide loss from the rumen, ought to be used in preference to fast-release compounds such as sulphate.

3.3.2.2. Phosphorus

Phosphorus (P) is a constituent of primary cell metabolites such as nucleotides, coenzymes etc. In vivo studies have mostly shown a significant depressive effect of P depletion in the rumen on the digestibility of the fibrous fraction of the diet (Durand et al., 1983; Breves and Holler, 1989). In vitro techniques have demonstrated that phosphorus is specifically required for the degradation of cell wall constituents and particularly for cellulolysis which seems to have a higher P requirement than hemicellulolysis and amylolysis (Komisarczuk et al., 1987).

In vivo, the available P supply to the rumen should be at least 5 g kg^{-1} OMD in order to optimise cell wall degradation. Assessment of the optimal dietary levels must involve factors influencing the secretion of salivary P, i.e. dietary P content, its absorbability, the concentrate to forage ratio and the physiological state of the animal (Durand, 1989). The absorbability of P contained in straws is not known but may be very low.

3.3.2.3. Magnesium

Magnesium (Mg) is essential to all microorganisms, activating many bacterial enzymes. Cellulases from R. flavefaciens in the rumen were shown to be activated by Mg^{2+} (Pettipher and Latham, 1979a). In vitro studies have shown that the addition of Mg improves cellulolytic activity (Durand and Kawashima, 1980).

Durand and Komisarczuk (1988) suggested that, in order to satisfy rumen microbial requirements, dietary Mg concentration should be in the range 1.5-2.5 g kg^{-1} OMD depending on *in situ* Mg solubility in the rumen. Untreated and alkali treated straw may supply about 1.2 and 0.9 g Mg kg^{-1} OMD respect- ively. They should therefore be supplemented with Mg, although more experimental data need to be obtained accurately to assess the amount of Mg required to optimise cell wall degradation.

3.3.2.4. Cobalt

Cobalt is required for the growth of rumen ciliates and is also integrated in the structure of vitamin B_{12} formed by bacteria (Bonhomme *et al.*, 1982). Saxena and Ranjhan (1978) obtained an increased cellulose degradation with a straw-based diet in calves with a cobalt supplementation of 0.1mg kg^{-1} DM.

Cobalt contained in straws is not likely to be available, hence it should be entirely supplied at 0.5-1.0 mg kg^{-1} DM.

3.3.2.5. Other trace elements

Trace elements play an important role in the metabolism of the rumen microbial population. The microbial requirements for iron, manganese, selenium and iodine appear to be similar to the dietary concentration required by the host (Lamand, 1978). Copper and zinc contained in straws are unlikely to be available and should be supplied in the mineral mix. It is worth noting that there is a narrow boundary between the stimulatory and toxic concentration of these elements.

3.3.3. Functions of minerals in the microbial rumen environment

The macrominerals contribute to the regulation of some physico-chemical characteristics of the rumen that are known to have an influence on fermentation.

3.3.3.1. Osmolarity

Osmotic pressure in the rumen is generally constant (250-280 mOsmol kg^{-1}). Major minerals contribute more to rumen osmolarity than do short chain fatty acids produced in the rumen. *In vitro*, cellulose degradation was decreased

when the osmotic pressure was greater than 400 mOsmol kg^{-1}. Alkali treatment of straws with sodium hydroxide can affect the osmotic pressure. Bergen (1972) reported that when the osmolarity of the in vitro media was increased above 400 mOsmol kg^{-1} with sodium salts, in vitro cellulose degradation was reduced by 80% or more.

3.3.3.2. Rumen dilution rate

Dilution rate can be increased by the addition of sodium salts. However, increased dilution rate has been observed to reduce the fibre digestibility of high forage diets. An explanation is that increased water intake, owing to sodium levels, diluted the bacterial population, hindering substrate-enzyme contact and hence reducing fibre digestion (Koes and Pfander, 1975).

3.4 Effect of other dietary ingredients on straw digestion

3.4.1. Digestible cellulose and/or hemicellulose

Alkali treatment of straw increases the rate of degradation of straw samples incubated in nylon bags in the rumen. Silva and Ørskov (1988a) showed that the degradation of untreated straw is improved when it is incubated in the rumen of animals fed alkali-treated straw compared with those fed untreated straw. It was suggested that this may be due to more favourable rumen conditions created by the increase in digestible celluloses and hemicelluloses of alkali-treated straw. Unmolassed sugar beet pulp or dried grass when given at a level of 150 g kg^{-1} straw DM increased both the rate and extent of degradation of untreated barley straw DM by 9 and 15% respectively (Silva and Ørskov, 1988b). Citrus pulp and soya bean meal had no effect on the degradation of straw, while fish meal appeared to have a small effect. In contrast, when ammonia treated straw was supplemented with molassed sugar beet pulp up to a rate of 0.45 of the total diet DM, there was no effect on DM degradation (Fahmy et al., 1984). It was suggested that ammonia-treated straw supplemented with sulphur and trace minerals cannot be greatly improved by addition of supplements of digestible cellulose/hemicellulose material.

3.4.2. Starch based supplements

The inclusion of high levels of starch rich concentrates in mixed diets has long been found to reduce cell wall degradation (Sutton, 1986). The reduction of cellulolytic activity can be due to decreases in the number of cellulolytic bacteria and/or their growth rates, the rate cellulases are synthesised and the enzyme activity. A decline of pH to values below 6.2, often observed with grain supplementation, can initiate these effects. Fahmy et al. (1984) supplemented ammonia treated straw with rolled barley up to an inclusion rate of 200 g kg^{-1} with no effect on straw intake and DM degradation. At higher inclusion rates, there was a significant decrease in DM degradation. This corresponded with a decline in rumen pH to below 6.2. Mould et al. (1983/84) showed that when the rumen pH was less than 6.1 rate of digestion of fibre was reduced.

Zorrilla-Rios et al. (1989) reported that supplementation of untreated and ammonia treated wheat straw with whole shelled maize (WSM) did not reduce straw intake or DM degradation at 10g kg^{-1} bodyweight$^{0.75}$, but did at the higher rate of 20g kg^{-1} bodyweight$^{0.75}$. The adverse effect of WSM on the digestion and intake of straw may be partially mediated by decreasing pH.

In vitro degradation of pure cellulose was much reduced by the presence of starch which lowered the pH from 6.5 to below 5.5. This effect was not observed when the pH was maintained at the control level (Durand, 1978). Van Gylswyk and Schwartz (1984) reported that the addition of starch increases the lag time in the degradation of grass fibre in vitro and that strains of B. succinogenes, which can use both starch and cellulose, preferentially digest starch. This bacteria when grown on glucose reduces its cellulase synthesis. This supports the fact that the number of cellulolytic bacteria does not alter greatly with increasing levels of fermentable carbohydrate. In vivo, there could be a selection for less pH-sensitive strains or for strains which preferentially use starch or glucose.

Stewart et al. (1979) concluded from in vitro studies on the effect of starch on fibre digestion that high amounts of starch have detrimental effects on the digestion of roughages, but that small amounts stimulate bacterial digestion of straw by enhancing the bacterial attachment to particulate matter.

Capper et al. (1989) showed that the effect of barley grain supplementation on organic matter intake of barley straw was dependent on variety. Other workers have shown that the type of cereal and level of processing will have differing effects on rumen pH change (Ørskov, 1981; Zorrilla-Rios et al., 1989). In order to try to optimise cell wall degradation of cereal straws through supplementation with energy sources, more research will be required on these topics.

3.4.3. Microbial growth factors

It has already been suggested that branched chain volatile fatty acids (BFA) stimulate cell wall degradation as they are required by cellulolytic bacteria strains (Russell, 1984). The formation of these BFAs from amino acids is dependent on cultural conditions such as the availability of an energy source. In vitro, addition of BFAs increased isolated plant cell wall digestion (Gorosito et al., 1985).

Stack and Cotta (1986) showed that addition of 3-phenylpropanoic acid to a defined medium dramatically increased cellulolytic activity of R. albus. The mode of action of this is still unknown. In vitro addition of B vitamins has improved the degradation rate of straw (Bouillier-Oudot et al., 1988).

It is clear that the availability of growth factors can have a great influence on the growth rate of certain bacteria, and that their supply is dependent on interactions between bacteria. Whether these compounds should be added directly to straw diets requires further research.

3.4.4. Yeast cultures

In vitro yeast cultures have been shown to increase the number of anaerobic bacteria five-fold and the number of cellulolytic bacteria two-fold (Dawson, 1987). Studies in vivo with sheep fed untreated straw and supplemented with yeast cultures demonstrated a slight increase in both rumen pH and total VFA production (Gray and Ryan, 1990).

3.4.5. Fungal cultures

Inclusion of a live fungal extract (Aspergillus oryzae, AO) in diets can increase the numbers of cellulolytic bacteria in the rumen (Wiedmeier et al.,

1987; Frumholtz et al., 1989). In vivo, the addition of AO fermentation extract to the straw diet increased the initial rate of straw degradation, but did not alter the final extent of rumen degradation (Fondevila et al., 1990). There was an overall increase in the total bacterial population in the rumen, but there was no increase in cellulolytic bacterial numbers as reported by Frumholtz et al. (1989). AO has been shown to exhibit cellulolytic activity (Walsh and Stewart, 1969). Fondevila et al. (1990) suggested that the improvement in rate of straw degradation with AO was due, not to an increase in cellulolytic bacteria counts, but to an improvement in their attachment and colonisation of straw.

Further work needs to be undertaken to confirm these results, and to elucidate the mode of action of AO.

3.4.6. Protein supplements

Some effects of protein supplementation on the degradation of straw have been discussed earlier in section 3.3.1.2.

A small supplement of fishmeal given to sheep fed untreated barley straw significantly improved organic matter digestibility compared with the unsupplemented control (Silva et al., 1989). This was not the case with a similar supplementation experiment using ammonia treated straw. Supplementation of untreated straw with both fishmeal and sugar beet pulp gave higher liveweight gains than when ammonia treated straw was fed alone. This has practical implications for situations where straw treatment is not convenient. Silva and Ørskov (1988b) previously showed fishmeal to have only a small effect on improving untreated barley straw degradation in the rumen. The difference seen in the improvement of straw digestibility with fishmeal supplementation between these two experiments may be due to an increase in amino acid supply to the host animal rather than to rumen changes in degradation of fibre. This is shown in the significant increase in overall digestibility in the first experiment and only a small increase in rumen degradability in the second.

McAllan (1991) showed that fishmeal supplementation significantly enhanced the digestibilities of the structural carbohydrates with both untreated and ammonia treated barley straw. The improvement in the straw digestibility due to the ammonia treatment and the fishmeal supplementation were additive.

Supplementation of untreated wheat straw with soya bean meal increased straw intake and average daily gains of steers. When ammoniated straw was substituted for untreated straw, the N in the ammonia treated straw was used for growth as efficiently as 500g of soya bean meal (Zorrilla-Rios et al., 1991). Supplementation of ammonia treated straw with soya bean meal did not improve DM degradation in the rumen (Fahmy et al., 1984). This indicates that the rumen environment created by ammonia treated straw supplemented with sulphur and trace minerals cannot be improved by addition of protein. In contrast, supplementation of sodium hydroxide treated straw with either soya bean meal or fishmeal to a level of 15g N kg^{-1} DM improved organic matter intake and straw organic matter digestibility to similar extents (Ng'ambi and Campling, 1991).

The variable results reported for protein supplementation of straws indicates the need for more extensive research in this area, including the effect of supplementing straws treated by other means.

4.0. ENERGY VALUE OF STRAW

As noted earlier (Table 4) the gross energy (GE) content of straw is approximately 18.5-18.8 MJ kg^{-1}DM and is similar to that observed in other forages. The extent to which the animal can utilise this energy is dependent primarily on the extent of straw cell wall degradation which takes place in the rumen, although further fermentation of cell walls may take place in the caecum and colon. It is also recognised (see Givens, 1987; Campling et al., 1990) that the energy available from straw can vary considerably. Some of this variability can be attributed to cereal species, variety and harvesting method.

4.1. Effect of cereal species on energy value

There is a considerable amount of data in the literature (see for example Staniforth, 1979) regarding the digestibility of UK grown straw as measured in vitro using the rumen fluid incubation procedure of Tilley and Terry (1963). However, there are fewer reports which provide measurements of digestibility or metabolisable energy (ME) in vivo. Table 5 provides a summary of recent digestibility and ME measurements made in vivo using sheep.

Table 5. Mean digestibility and energy values of UK cereal straws measured *in vivo* (SD in parenthesis).

Cereal species	n samples	Organic matter digestibility	ME ($MJkg^{-1}$ DM)	Reference
Wheat	2	0.45(0.074)	6.0(0.89)	Wainman *et al*. (1984)
	1	0.34[1]	6.0	Reid *et al*. (1988)
	62	0.45(0.052)	6.0(1.10)	Givens *et al*. (1989)
Barley	4	0.43(0.014)	5.8(0.43)	Wainman *et al*. (1984)
	4	0.44(0.036)[1]	7.4(0.29)	Reid *et al*. (1988)
	51	0.48(0.055)	6.5(1.21)	Givens *et al*. (1989)
Oats	2	0.45(0.074)	6.0(0.89)	Wainman *et al*. (1984)
	5	0.51(0.009)	7.0(1.14)	Givens *et al*. (1989)

1, Dry matter digestibility.
n, Number of samples.

The results summarised in Table 5 show clearly that organic matter digestibility (OMD) and ME contents can vary considerably within cereal species. This suggests that the traditional belief of the inferiority of wheat relative to barley straw does not always hold true. In the report of Givens *et al*. (1989), oat straws had significantly ($P<0.01$) higher digestibility values than wheat or barley straws, although the findings of Wainman *et al*. (1984), with smaller numbers, did not show this effect. Values in Table 5 are supported by digestibility measurements *in vitro* by Kernan *et al*. (1979) and Adamson and Bastiman (1984) both of whom found evidence that wheat straws could be of equal or greater digestibility than barley straw.

It should be noted that the measurement of whole tract digestibility and ME content of straws poses a number of problems not encountered with other forages. These problems have been reviewed in detail by Cottyn *et al*. (1989) and often include the need to calculate the values for the straw by difference when its inclusion rate in the diet is low, and the need to ensure that the total diet is adequate in nitrogen and sulphur to optimise cellulolytic conditions in the rumen (see also section 3.1 of this review). Givens *et al*. (1990) also showed that substantial differences in digestibility could occur between laboratories and within a laboratory. In the same study it was shown that estimating digestibility by difference led to a greater error of determination than feeding straw alone *ad libitum*. The difficulties measuring digestibility and ME *in vivo* are likely to have

contributed to at least some of the variation in the mean values shown in Table 5.

The nylon bag method (Chenost et al., 1970) has been widely used as a method for studying degradation of straws in the rumen. In terms of providing information on effect of cereal species, the results of Tuah et al. (1986) are not entirely in agreement with the whole tract digestibility measurements in Table 5. In the study of Tuah et al. (1986), mean DM losses of 49.9, 37.4 and 48.7% were recorded for 19 barley, 14 wheat and 11 oat straws respectively after 48h of incubation, although the values for barley straw were obtained using sheep whereas the others were from steers. The superiority of oat straws over wheat was largely accounted for by differences in the amount of water soluble material (4.0, 10.6% DM; wheat, oats). In marked contrast, the work of Shand et al. (1988) showed higher 48h losses for 12 wheat (44.1%) than 6 oat straws (38.1%). This was despite the oats straws having higher concentrations of immediately soluble material.

Jewell et al. (1986) used an enzyme solubility procedure for comparing the digestibility in vitro of three samples each of winter wheat, winter barley and spring barley. The mean DOMD contents were respectively 311, 348 and 352 g kg^{-1} DM, the value for winter wheat being significantly ($P<0.05$) lower than that for spring barley. Notably, in the study of Jewell et al. (1986), differences in enzyme solubility were not well correlated with the proportions of botanical fractions of the straws whereas Thiago and Kellaway (1982) attributed large differences in in vitro rumen liquor digestibility of wheat and oat straws to differences in leaf and stem proportions.

Whilst in general, oat straws tend to have higher digestibilities than other species, straw species is clearly not a reliable guide even to the ranking of straw quality.

4.2. Effect of cereal variety on energy value

Until relatively recently, the effect of variety within species on the energy value of straws has not been considered extensively. Jewell et al. (1986) showed that variety could significantly influence the enzyme solubility of winter wheat straws, with Aquila and Avalon having the lowest (276 g kg^{-1}DM) and highest (364 g kg^{-1}DM) values respectively in this study.

An extensive study (Tuah et al., 1986) of different straw varieties grown in the same year under identical conditions showed conclusive evidence of varietal effects on DM loss during incubation in nylon bags in the rumen. The results of the best five varieties of wheat, barley and oats straws are given for illustrative purposes in Table 6.

Table 6. Mean dry matter loss (DML) after 48h incubation for varieties of wheat, barley and oats straws (after Tuah et al., 1986).

Cereal species	Variety	DML (% DM incubated)
Wheat	Stetson	40.2
	Armada	39.1
	Brigand	38.7
	Longbow	38.4
	Brimstone	37.6
Barley	Doublet	48.0
	Corgi	47.7
	Tasman	46.4
	Natasha	46.0
	Heriot	45.4
Oats	Maris Tabard	60.7
	Saladin	58.7
	Ballad	56.4
	Cabana	56.3
	Matra	54.3

Later work using straws from the same location (Shand et al., 1988) indicated that the same variety may have a substantially different value between years. Also, although the ranking of varieties was generally similar, there were some cases where ranking was considerably different.

Ørskov et al. (1990) studied the consistency of varietal differences in spring barley and winter wheat across three years and in oats and winter barley across two years. They concluded that for all varieties there were large year to year differences in rumen degradation, although in most cases the ranking of varieties was similar. More recently, the effects of site (i.e. where grown) and variety on the dry matter loss in the rumen after 24h have been studied by Wright and Hughes (1991). These workers used 12 varieties of spring barley straw grown on eight sites covering geographical extremes of England and Wales. For DM losses after 24h incubation in the rumen, differences between sites were larger than between varieties and effects of site accounted for 69% of the total variability compared with only 9% for variety. The site x variety interaction was not significant. Despite the large influence of site there was reasonable consistency in the performance of individual varieties at different sites. For example, variety Digger had the overall highest degradability whereas varieties Blenheim, Ilka, Triumph and Klaxon consistently produced low rumen degradabilities. Notably, protein and cell wall fractions were much less consistent from site to site. It is interesting to note that there appears to be little or no correlation between the extent of degradability of straw and grain yield (Tuah et al., 1986; Shand et al., 1988) suggesting the possibility of breeding varieties for straw quality without affecting yield. This subject has also been extensively discussed by Capper (1988).

It now seems clear that variety can have a substantial influence on the energy value of cereal straws, although differences between varieties can be much smaller than differences between years or sites. It is thus not possible to ascribe a unique value to any individual variety.

4.3. Effect of botanical fractions of straw on energy value

Work undertaken in Syria and the UK (Capper et al., 1985) with barley straw indicated that leaf:stem ratio has a substantial effect on digestibility in vitro using rumen fluid. The work indicated that leaves are more digestible than stems and, in the case of the UK straws, stem height was the major determinant of leaf:stem ratio, short stems being favoured. Studies by Ramanzin et al. (1986) using the nylon bag technique confirmed these findings for two varieties of barley straw. Further investigations (Shand et al., 1988) confirmed that leaves of wheat and oat straws were also of higher

degradability than stems. Table 7 summarises some of the findings of Shand et al. (1988).

Table 7. Mean values for 48h degradability (deg), the immediately soluble fraction (a), the insoluble but degradable fraction (b) and the rate of degradation (c) for the botanical fractions of oats and wheat straw. (after Shand et al., 1988).

Botanical fraction	48h deg (% DM)	a (%)	b (%)	c (h^{-1})	a+b (%)
Oat straws[1]					
Leaves	50.1	4.0	56.7	0.035	60.7
Internodes	27.1	11.6	30.5	0.015	42.1
Nodes	49.5	8.1	45.5	0.051	53.6
Chaff	67.9	-5.8	80.8	0.058	75.0
Wheat straws[2]					
Leaves	61.5	-3.8	77.2	0.042	73.4
Internodes	33.0	7.6	37.2	0.026	44.8
Nodes	51.4	9.8	45.1	0.053	54.9
Chaff	40.3	10.0	37.6	0.034	47.6

1, Mean of 6 varieties
2, Mean of 12 varieties

The figures in Table 7 highlight not only the greater extent of digestion of the leaves than the stems (internodes), but also the faster rate of digestion. Other work (Bhargava et al., 1988) has identified that within the leaves of barley straws, the leaf blade has a higher potential degradability and rate of degradation than the leaf sheath. Goto et al. (1991) have studied the reasons for differences between botanical fractions in terms of specific cell types and their organisation.

Shand et al. (1988) also reported that whilst in wheat, high quality leaves were moderately correlated with high quality stems ($r = 0.70$), with oats the correlation was very poor ($r = 0.15$). Information on this aspect appears to be scarce but if the poor correlation is confirmed by other studies, it may be possible to select for high quality leaf independent of stem quality. Differences in the quality of leaves and stems may also lead to the possibility of mechanical straw fractionation with the leaves being used for animal feed and the stems for industrial applications such as paper and hardboard manufacture (Rexen and Munck, 1984). Whilst not of relevance to the UK, it is worth recording that whilst the digestibility of leaves is

greater than stems in temperate cereals, the opposite is the case with rice straw (Capper, 1988).

4.4. Effects of agronomic and harvesting practice on energy value

4.4.1. Effect of nitrogen fertiliser

Although there seems to be little information from the UK on the effect of rate of fertiliser nitrogen applied to cereal crops on the digestibility of the straw, some studies from Canada have been reported. In particular, Kernan et al. (1984) compared applying nitrogen to nine wheat varieties at either 0, 56 or 224 kg ha^{-1} and showed that the proportion of leaf significantly increased with increasing nitrogen. This increase was, however, small although increased nitrogen also tended to increase slightly the organic matter digestibility in vitro (rumen fluid method) of the leaves (at most from 0.48 to 0.51).

4.4.2. Cutting height

Increasing the cutting height has been shown (Smith et al., 1975) to substantially reduce straw yield. Since this should be due almost entirely to a reduction in the proportion of stem, increased cutting height should lead to increased digestibility of the harvested straw. The authors have not found any data to substantiate this.

4.4.3 Fungal disease

There appears to be little information on the effect of fungal disease of straw on its digestion. However, with decreased use of fungicides and increased land in set-aside, there may be increased risk of fungal diseases affecting straw. This is an area worthy of study.

4.5. Effect of processing and treatment on energy value

There are many physical and chemical treatments which have been used in attempts to enhance the feeding value of straw. Han and Garrett (1986) listed 6 physical and 26 chemical treatments in addition to biological treatments involving microorganisms, enzymes and fungi. Sundstøl (1988) has recently reviewed many of the methods and, in the present review, it is

intended to examine only the treatments which are or may be of significance in the UK.

4.5.1. Sodium hydroxide

Sundstøl (1988) has given an overview of the main methods for sodium hydroxide treatment of straw. These are essentially divided into wet and 'dry' methods of treatment. Much of the straw treated with sodium hydroxide in the UK is processed by a 'dry' method usually involving a commercial treatment machine. Recent unpublished studies at the ADAS Drayton, Feed Evaluation Unit on farm methods of application have been compared and this confirmed that commercial treatment machines provided by far the most accurate means of adding sodium hydroxide. They are also preferable because of safety aspects of handling this chemical.

In vivo and in vitro digestibilities are the most frequently used measurements for assessing the effect of sodium hydroxide. Table 8 illustrates the effect of treatment with sodium hydroxide at 45g kg^{-1} DM using the recent data of Moss et al. (1990).

Table 8. Effect of sodium hydroxide on the digestibilities and digestible energy contents of wheat, barley and oat straws (after Moss et al., 1990).

	Wheat		Barley		Oats	
	UT[1]	T	UT	T	UT	T
DOMD[2] (g kg^{-1})	371	555	495	681	447	538
Organic matter digestibility	0.40	0.63	0.53	0.76	0.48	0.62
Digestible energy (MJkg^{-1}DM)	6.3	9.2	9.4	11.9	7.6	9.6

1, UT, untreated; T, treated.

2, Digestible organic matter in dry matter.

These results indicated that the average increase in DOMD content was 161 g kg^{-1} and this increase was not influenced by the value of the untreated

material. Increases of this magnitude are typical of those reported for sodium hydroxide treatment at 30-50 g kg^{-1}DM (see Alawa and Owen, 1984).

In addition to measurements of whole tract digestibility, it has been shown (Lindberg et al., 1984) that sodium hydroxide treatment can increase the fraction of straw which is soluble and also increase the rate of digestion of the insoluble fraction in the rumen. These factors are likely to contribute to the observed increased voluntary intake of sodium hydroxide treated straw by sheep (Alawa and Owen, 1984) and cattle (Ng'ambi and Campling, 1991).

4.5.2. Ammonia

Ammonia is somewhat less corrosive than sodium hydroxide and the use of ammonia for straw treatment has been extensively researched. Both anhydrous and aqueous ammonia have been used (see Sundstøl, 1988) normally at rates of 30-35 g kg^{-1}DM. In Europe, most treatment with anhydrous ammonia is undertaken by injecting the ammonia into stacks of straw sealed by polyethylene sheets, although some commercial treatment ovens are also used.

Treatment of straws with ammonia has been shown to increase digestibility and intake although the responses to treatment are normally rather less than for sodium hydroxide, despite the fact that nitrogen content is also increased. Treatment of UK straws with ammonia at 35g kg^{-1}DM in an oven by Givens et al. (1988) gave the results shown in Table 9.

Table 9. Treatment of wheat, barley and oats straw with ammonia (after Givens et al., 1988).

	Wheat		Barley		Oats	
	UT[1]	T	UT	T	UT	T
DOMD[2] (g kg^{-1})	421	528	441	548	506	562
Organic matter digestibility	0.45	0.56	0.46	0.51	0.54	0.60
Digestible energy (MJkg^{-1}DM)	7.7	9.2	8.1	9.5	9.0	10.1

1, UT, untreated; T, treated.

2, Digestible organic matter in dry matter.

In the same experiment, the nitrogen content of treated straws was about three times higher than in the untreated material. Also, it was noted that the degree of upgrading achieved in an individual straw was highly dependent on its digestibility before treatment, poorer straws upgrading the most. A similar relationship was observed for the effect of ammonia on the rumen degradability of cellulose in varieties of spring barley straw (Goto et al., 1991).

Overall increase in DOMD content was approximately 100g kg^{-1}, although this was somewhat lower than the response observed by some other workers. For example, Lawlor and O'Shea (1979) and Williams et al. (1984) reported increases in DOMD of 158 and 170 g kg^{-1} respectively although these straws had lower initial digestibilities than the straws of Givens et al. (1988).

The effects of ammonia on the rumen degradation of straws has also been extensively studied (e.g. Tuah et al., 1986; Silva and Ørskov, 1988a) and Everington and Givens (1988) demonstrated that the main effect of treatment was to increase the immediately rumen soluble fraction of the straw although the rate of degradation of the insoluble fraction was unchanged. It is noteworthy that Van Soest and Mason (1991) reported that, in ammonia treated grasses, the solubilised fraction was not subsequently digested. As a result they questioned the use of the nylon bag and in vitro procedures for evaluating upgrading by ammonia. Information as to the situation with ammonia treated straw is required.

Treatment with ammonia has also been shown to increase voluntary intake of straws. Jewell and Campling (1986) showed that the intake by cattle (235-350kg live weight) of wheat straw treated with aqueous ammonia was increased by 25%. Interestingly, Ørskov et al. (1988a) indicated that for Friesian cows increases in voluntary intake of ammonia treated barley straw were closely related to the rumen degradation characteristics of the straws (see also Section 5.0).

4.5.3. Urea

Urea is a relatively safe chemical to handle and use of urea to upgrade straw relies on its subsequent enzymatic hydrolysis to ammonia by naturally occurring or added urease enzymes. Sherwood and Owen (1983) compared the effectiveness of urea and ammonia for upgrading cereal straw. Some of their

results using wether sheep (38kg) are summarised in Table 10. The authors concluded that urea was less effective than ammonia for improving intake and that improvements in digestibility were temperature dependent. Another disadvantage of urea treatment is that hydrolysis of urea to ammonia is moisture dependent. Williams et al. (1984) showed that, whilst hydrolysis of urea was 100% when applied to moist straw (DM 550 g kg^{-1}), this was reduced to only 37% with dry straw (DM 750g kg^{-1}). The requirement for high moisture contents and high temperature for optimum hydrolysis probably limits the use of urea in temperate countries.

Table 10. Comparison of urea with ammonia for upgrading cereal straws (after Sherwood and Owen, 1983).

	Treatment method				
	U[1]	NH_3[2]	UT1[3]	UT2[4]	SED
Straw intake ($gDMd^{-1}$)	679	782	643	605	28.4
Organic matter digestibility	0.38	0.49	0.42	0.48	0.019

1, Untreated; 2, Ammonia treated 35g kg^{-1}DM; 3, Urea treated, 70g kg^{-1}DM ensiled at DM content of 500g kg^{-1} for 8 weeks; 4, Urea treated by dipping bales in urea solution (45 min in 32g l^{-1} solution) followed by 3 weeks storage.

4.5.4. Enzymes

The use of enzymes for upgrading straw has not been studied extensively, but it is referred to in this review because of the potential of the process. The main advantages of enzymatic methods are claimed to be much greater control of the end products formed after treatment and little or no potential environmental pollution (Nakashima and Ørskov, 1989).

The two main approaches to the use of enzymes recently examined have been related to the use of polysaccharidase and ligninase enzymes. Nakashima et al. (1988) examined the use of polysaccharidase enzymes on rice straws and showed that enzyme treatment increased the immediately rumen soluble fraction and the rate of degradation of the straws, although potential degradability was unaffected. The enzyme treatment was unaffected by the moisture content

of the straws over the range 500-700 g kg^{-1}. Similar effects have been observed when ensiling barley straw with cell wall degrading enzymes (Nakashima and Ørskov, 1989) although, in this experiment, no effect on rate of digestion was observed.

Recently Khazaal et al. (1990) have examined the effect of treating barley straw with a ligninase enzyme produced from the fungus Phanerochaete chrysosporium. In this experiment, little effect of ligninase enzyme was detected in terms of in vitro organic matter digestibility, but the authors suggested that the optimum condition for the enzyme may not have been achieved.

It is clear that much further work is required into the use of enzymes for enhancing the energy value of straws.

5.0 VOLUNTARY INTAKE OF STRAW

The supply of energy and nutrients from straw to the animal depends not only upon the concentration of available energy in the material but also on the amount consumed. Whilst in some circumstances straw is fed in fixed daily amounts, there are many situations where straw is fed ad libitum. It is, therefore, important to understand the factors influencing the voluntary intake of straws. These factors include the straw digestibility, rumen degradability, physical form, chemical processing and the influence of other dietary components.

5.1 Effect of digestibility/degradability

There are many references in the literature to the fact that intake of forages is generally positively related to digestibility in vivo and in vitro. Studies by Ørskov et al. (1988b) confirmed this general relationship for barley and wheat straws fed to cattle. Their results for untreated straws are shown in Table 11. However, in the same experiment it was shown that the degradation constants obtained from the use of the nylon bag technique were related more closely to intake than was whole tract digestibility. Aspects of this are discussed later (Section 6.0).

Table 11. Effect of digestibility *in vivo* on voluntary intake by cattle of wheat and barley straws. (after Ørskov *et al.*, 1988b).

Cereal species	Dry matter digestibility ($g\ kg^{-1}$)	Voluntary intake ($kg\ DM\ d^{-1}$)
Winter wheat	343	4.57
Winter barley	409	3.43
" "	412	3.56
Spring barley	452	4.43
" "	484	5.16

5.2 Physical form

There is much evidence (see Walker, 1984 for review) that grinding, chopping or pelleting straw to small particle size increases voluntary intake. Owen (1978) has, however, pointed out that particle size reduction is a poorly defined term even when grinding takes place through a given screen size. The increased intake seen following particle size reduction seems to arise essentially from increased rate of passage through the digestive tract (Sundstøl, 1988), although chewing time to reduce particle size to a size suitable for digestion is also very much reduced (Walker, 1984).

It may be noted that milling and chopping of straws whilst increasing intake does not increase digestibility, indeed some reduction in digestibility may occur.

5.3 Chemical treatment

Some aspects of this have been discussed earlier (Section 4.5). Chemical treatment notably with sodium hydroxide and ammonia have given consistently increased voluntary intakes of straw. Using a dry sodium hydroxide treatment, Kristensen (1982) concluded that intake increased with increasing application rates up to 40-50 $g\ kg^{-1}$ DM, above which it declined. Effect of ammonia treatment on voluntary intake of sheep and cattle is illustrated in

Table 12 from the work of Silva et al. (1989). The results in Table 12 also illustrate the fact that ammonia treatment had a greater effect on intake in sheep than cattle. As pointed out by the authors, this has not been a common observation.

Table 12. Effect of ammonia treatment of barley straw on voluntary intake by sheep and cattle (after Silva et al., 1989).

Species	Daily intake (kg DM animal^{-1})	
	Untreated	Ammonia treated
Sheep (35kg)	0.414	0.729
Cattle (319kg)	4.75	6.09

5.4 Opportunity for selection

It has been known for some time that species such as sheep and goats display selective feeding behaviour and are able to select parts of forage of better quality. This selection has also been demonstrated with sheep and goats fed straw (Wahed and Owen, 1986). Bhargava et al. (1988) showed with sheep (55kg live weight) that when they were allowed to leave uneaten proportionately 0.2, 0.3, 0.4, 0.5 and 0.7 of the straw offered, the amount of leaf blade in the material consumed increased linearly with the amount of excess allowance. Owen et al. (1990) have also demonstrated selective feeding of straw by sheep and goats and have shown the importance of the amount of straw offered. Table 13 illustrates some of the results of Owen et al. (1990). Digestible organic matter intakes were estimated from in vitro digestibility measurements of straw offered and refused. From these measurements, it can be calculated that the DOMD contents (in vitro) of the consumed material were 467, 561 and 572 g kg^{-1} for the 18, 54 and 90g DM kg^{-1} live weight d^{-1} treatments respectively. Owen et al. (1990) also demonstrated that the same effect did not occur with cattle.

Table 13. Intake and selection of barley straw by wether sheep offered increasing amounts of straw. (after Owen et al., 1990).

	Straw offered (gDM kg^{-1} live weight d^{-1})		
	18	54	90
Straw offered (g DM d^{-1})	957	2787	4702
Straw refused (% of offered)	20.8	64.7	75.1
Straw intake (g DM d^{-1})	758	984	1171
Digestible OM intake (g DOM d^{-1})	354	552	670

DOM, Digestible organic matter.

On the basis of the above results, it appears that permitting sheep to reject large amounts (i.e. >50%) of offered straw allows them to select the most nutritious part of the plant and increase daily intake of both DM and digestible OM. The magnitude of the effect appears to be similar to upgrading straw with ammonia. Aspects of this clearly need further study.

5.5 Effect of dietary supplements

Since straws are naturally deficient in nitrogen and certain minerals, supplementation of these nutrients is normally required to optimise rumen conditions for straw digestion. This area has been covered in detail in Section 3.3. Failure to supplement with these nutrients may lead to a reduction in voluntary intake (Ribeiro, 1989).

Whilst straw intake is normally reduced by feeding supplements (Sundstøl, 1988), there have been reports indicating that some supplements can increase straw intake. Silva et al. (1989) showed that, when feeding untreated barley straw, supplementing sheep with about 60g d^{-1} of unmolassed sugar beet pulp significantly ($P<0.05$) increased straw intake from 414 to 505g DM d^{-1}. There was also a non-significant trend for increased straw intake with supplements of fishmeal and fishmeal plus sugar beet pulp. Since the response with sugar beet pulp may be related to an enhancement of straw degradation in the rumen, as observed by Silva and Ørskov (1988b), it would seem important for further studies to examine in more detail the relationships between straw degradation, intake and type of supplements.

6.0 PREDICTION OF ENERGY VALUE AND VOLUNTARY INTAKE

From the foregoing, it is clear that the energy value and intake characteristics of straws can vary considerably for a variety of reasons. Thus, for maximum utilisation of straw, it is important that techniques are available which can predict important measures of nutritive value, preferably without recourse to using animals.

6.1 Prediction of digestibility

There have been many reported attempts to use the concentration of cell wall fractions such as crude fibre (Barber et al., 1984; Reid et al., 1987), neutral and acid detergent fibre (Sundstøl et al., 1978; Barber et al., 1984) and acid detergent lignin (Wainman et al., 1984) to predict digestibility of straws in vivo. All these attempts have shown that cell wall fractions provide very poor predictions.

Despite these findings there are indications that more complex analyses may yield useful information. For example, Givens et al. (1988) showed that the determination of cellulose in isolated cell walls correlated well with digestible energy measurements in vivo in untreated and ammonia treated straws. Also, Mason et al. (1988) have shown that ferulic acid content of straw cell walls was able to clearly distinguish between untreated and ammonia treated straws. Moss et al. (1990) also reported that buffer extractable phenolics clearly identified the difference in digestibility of untreated and sodium hydroxide treated straws.

Probably the most extensively used laboratory method for assessing straw digestibility is the in vitro digestion technique using rumen fluid-pepsin, based essentially on the method of Tilley and Terry (1963). The literature contains many reports on its use although relatively few provide relationships with measurements in vivo. Notably, exceptions include the studies of Den Braver (1976), Sundstøl et al. (1978) and Moss et al. (1990).

In vitro techniques which utilise cell-free cellulase/xylanase type enzymes for assessing straw digestibility have also been reported (Jewell et al., 1986; Reid et al., 1988). De Boever et al. (1988) compared the use of a pepsin-cellulase method with the rumen-fluid procedure in 16 straws and concluded that the rumen fluid method provided a better relationship with

digestibility *in vivo*. More recently, Ørskov and Reid (1989) and Givens *et al*. (1991) have compared several enzyme-based methods with rumen fluid-pepsin and the use of near-infrared reflectance spectroscopy (NIRS) for predicting digestibility *in vivo*. A summary of these two studies is shown in Table 14 by means of ranking the methods according to the variance accounted for (R^2).

Table 14. A comparison of various *in vitro* methods and NIRS for predicting digestibility in straws *in vivo*.

Method	R^2(%)	Number of samples	Reference
Rumen fluid-pepsin	81.0	10	Ørskov and Reid (1989)
Neutral detergent-cellulase	65.6	10	
NIRS	59.3	10	
NIRS	74.1	81	Givens *et al*. (1991)[1]
Rumen fluid-pepsin	61.2	81	
Neutral detergent-cellulase	60.8	81	
Pepsin-cellulase	60.2	81	

1, Values obtained during calibration.

In the comparison of Givens *et al*. (1991), NIRS was shown to predict digestibility *in vivo* most accurately. Despite this, it accounted for only about 65% of the variance in *in vivo* digestibility when validated on an independent set of samples. This is lower than reported for other forages and may relate to the increased error of determination of digestibility *in vivo* for straws compared with some other forages (see Section 4.1). Despite this, it would seem that all the methods cited in Table 14 and especially NIRS are still valuable tools for predicting straw digestibility and energy value. It seems probable that enzyme methods could be enhanced by more careful selection of enzyme activities (see Chesson and Murison, 1989) and the use of NIRS has considerable scope for development.

6.2. Prediction of voluntary intake and animal performance

The rumen fluid-pepsin procedure has also been used to predict animal performance. For example, Adamson and Bastiman (1984) found that it provided a good estimate of performance in cattle when straw was fed ad libitum. More recently, several reports (Reid et al., 1988; Ørskov et al., 1988b; Ørskov and Reid, 1989; Ørskov et al., 1991) have compared in vivo and in vitro digestibility methods with rumen degradation characteristics for predicting intake and animal performance. It should be noted, however, that the first three papers referred to all relate to the same experiment. A summary of some of these findings is shown in Table 15.

The results in Table 15 highlight the superiority of degradation constants over digestibility in vivo, although it may be noted that the number of straws used was small. Clearly any widespread use of the prediction equation given by Ørskov et al. (1988b) would require wider validation. In vitro digestibility methods performed almost as well as degradation constants despite the fact they do not estimate degradation rate. Clearly, further development of in vitro procedures which provide an estimate of digestion rate would seem to be important.

Table 15 also indicates that NIRS has potential for predicting intake and performance, although from the paper cited it is not clear how the NIRS procedures were carried out and for robust relationships NIRS requires large populations. Nevertheless, NIRS has considerable potential for estimating intake and performance and research to develop sound NIRS calibrations for degradation characteristics would seem essential. Whilst the data referred to point the way in which future research may develop, at present there appear to be no widely based, independently validated relationships available for predicting straw intake or animal performance.

Whilst the nylon bag technique appears to hold most promise for predicting intake, it is not strictly a laboratory procedure and suffers from being a non-standard technique which can give substantially different results between different laboratories.

Table 15. Comparison of various procedures to predict straw intake and animal growth rate.

Method	R^2% for		Number of straws	Reference
	Intake	Growth rate		
48h degradability	81.0	-	10	Ørskov et al. (1988b)
(a+b)[1], c	79.2	82.8		
a, b, c	77.4	90.3		
Rumen fluid-pepsin	79.2	86.5	10	Reid et al. (1988)
Neutral detergent-cellulase	77.4	90.3		
NIRS	74.0	75.7		
In vivo digestibility	49.0	59.3		

1, Degradation constants from the nylon bag technique.

7.0 PROTEIN VALUE OF STRAW

The protein value of cereal straws is low. An example of the range of crude protein (CP) contents recorded in cereal straws is shown in Table 16.

7.1 Effect of species/variety on protein value

There have been many reports that differences exist in the nutritive values of different varieties of wheat, barley and oat straws (Kernan et al., 1984; Hartley et al., 1984). Tuah et al. (1986) compared the CP content of 19 varieties of spring barley straw, 14 varieties of wheat straw, 11 varieties of oat straw and one variety of triticale straw grown on one site under identical agronomic conditions. The oat straws had the highest mean CP content followed by the spring barley and wheat straws (33.0, 30.1, 25.9 g

kg^{-1} DM respectively). The mean values and ranges of CP content are shown in Table 17.

Table 16. Average crude protein contents of cereal straw (after MAFF, 1990).

Straw type	Crude protein (g kg^{-1} DM)				Number of samples
	Mean	SD	Min.	Max.	
Barley straw					
Spring	42.6	12.9	20.0	71.0	31
Winter	37.6	11.4	26.0	59.0	16
Oat straw					
Spring	29.0	7.1	24.0	34.0	2
Winter	37.0	11.9	20.0	48.0	4
Wheat straw					
Spring	36.5	7.9	25.0	43.0	4
Winter	39.1	10.5	22.0	78.1	60

Table 17. Crude protein content of barley, wheat and oat straws.
(after Tuah et al., 1986)

	Straw		
	Spring barley	Wheat	Oats
n	19	14	11
Mean	30.1	25.9	33.0
SD	2.24	2.26	3.26
Min.	25.4 (Golden Promise)[1]	22.5 (Brock)[1]	26.3 (Rhiannon)[1]
Max.	33.1 (Natasha)[1]	29.4 (Amarda)[1]	38.1 (Leanda)[1]

n is number of samples. 1, Variety.

It is evident from the results that variety has a strong influence on CP content of the resulting straws and that certain varieties of wheat and barley straw can have CP contents equivalent to the mean CP value of oat straws. In a similar experiment, Ramanzin et al. (1991) measured the CP content of nine varieties of barley and wheat straws grown under identical agronomic conditions. The barley straws had a mean CP content of 39 (±11) g kg^{-1} DM compared with 43 (±13) g kg^{-1} DM for the wheat straws. The high standard deviations indicate considerable variation between varieties for CP content. It is worth noting that wheat straw had higher CP contents than barley straw which is the opposite of that found by Tuah et al. (1986). Givens et al. (1989) also found the CP content of straws to be the highest in oats followed by barley and wheat species respectively. In this study, there was no recorded year effect on CP content, but there was a significant effect of county of harvest. Wright and Hughes (1991) also showed geographical location to have a significant effect on the CP content of spring barley straws with a lesser effect of variety.

7.2 Effect of processing/treatment on protein value.

Improving the feeding value of straws by the addition of chemicals is well accepted, and has received considerable attention, although there has been little reported on the effect on protein value.

7.2.1 Ammoniation

7.2.1.1 Anhydrous ammonia

Treatment of straw in a sealed stack with 3-3.5% anhydrous ammonia is a commonly used commercial method of upgrading straw. Cottyn and de Boever (1988) showed 3% anhydrous ammonia to improve the CP content of barley and wheat straw by 19 and 73 g kg^{-1} DM respectively, with an average improvement of 51 g kg^{-1} DM. This improved nitrogen enrichment with treatment improved the apparent protein digestibility, resulting in a digestible CP content of 32 g kg^{-1} DM on average for the treated straw compared with 1g kg^{-1} DM for the untreated material. Sundstøl et al. (1978) indicated that ammoniation raised the CP content by 50-60 g kg^{-1} DM. Mann et al. (1988) reported an improved CP content of 34 g kg^{-1} DM with ammoniation of wheat straw. There appears to be little evidence in the literature of the initial CP content of

the untreated straw being related to the eventual CP content of the ammonia treated straw.

Treatment of straw with ammonia not only increases the digestibility but also the nitrogen content. Reports indicate that not all this extra nitrogen can be degraded as it is tightly bound to the straw and not released in the rumen (Solaiman et al., 1979). Therefore, the extra nitrogen bound to straw during treatment can only be considered to be partly soluble in the rumen. For untreated and ammonia treated straws, Hvelplund (1985) studied in sacco the extent of nitrogen degradation in the rumen and the subsequent digestion in the intestines. The work showed improved rumen degradation of nitrogen with ammonia treatment, although only 77% of the ammonia bound to the straw was degraded in the rumen. The disappearance of nitrogen in the small intestine from rumen undegraded material of both untreated and ammonia treated straw was similar and limited, indicating a low value of the undegraded protein in straw.

Hvelplund (1989) suggested that, for straws, the measuring of nitrogen degradability by means of the nylon bag technique was inadequate due to the relative importance of the microbial population which is attached to both straw particles and nylon bags. Other direct methods of measurement of microbial synthesis are complex, hence further research is required for a better evaluation of nitrogen degradability.

7.2.1.2 Anhydrous ammonia plus water and temperature

There is wide variation in the efficacy of commercial chemical upgrading processes (Ibbotson et al., 1983/1984). Factors responsible for this variation include species and variety of cereal (Mason et al., 1988; Givens et al., 1988), temperature and duration of treatment, amount of ammonia employed and moisture content of the straw (Westgaard, 1981; Sundstøl and Coxworth, 1984). Mason et al. (1990) showed that thermo-ammoniation (90°C for 24h) of wheat straw with different rates of ammonia and water improved the CP content of the straw. Each increment of ammonia raised the CP content and additions of water further enhanced this effect. Responses were small, although once the rate of ammonia application exceeded 20g kg^{-1} DM, differences between 40 and 80 g kg^{-1} DM were not significant.

Schneider and Flachowsky (1990) showed that the variation in nitrogen content of ammonia treated straw is accounted for by ammonia level, straw moisture and temperature respectively. The efficiency of nitrogen retention in straw treated with ammonia declined with increasing application rate of ammonia (89, 67 and 51% retention for 15, 30 and 45g NH_3 kg^{-1} DM respectively), and after airing, the total nitrogen content declined to relatively constant values, irrespective of the content before airing. The ammonia in treated straw is either gaseous, water-bound or tightly bound to the straw and both forms will be lost at differing rates on exposure to air. Treatment conditions will affect the type and consequently the strength of nitrogen binding (Benzing-Purdie and Ripmeester, 1987) and this may affect the degree of nitrogen loss and nitrogen utilisation by rumen microbes. Further research is necessary to investigate the microbial availability of different nitrogen fractions in ammoniated straw according to various treatment conditions.

7.2.1.3 Urea

Sherwood and Owen (1983) showed urea treatment of cereal straw to be less effective than ammonia treatment. There is little evidence in the literature of the effect on protein value of urea treatment, although it is possible that some of the nitrogen could still be in the form of urea if hydrolysis to ammonia has not been complete.

7.2.2 Sodium hydroxide treatment

Treatment with sodium hydroxide (NaOH) has been shown to be an effective method for upgrading low quality straws (Owen, 1981), though addition of NaOH exacerbates the N deficiency which already exists in straw (Ørskov and Grubb, 1978). Moss et al. (1990) showed NaOH treatment to decrease the crude protein content of 10 samples of cereal straws, and tended to increase the apparent digestibility of crude protein, although the differences did not reach statistical significance.

7.3 Effect of botanical fractions on protein value

As already discussed, straw is a very heterogenous feedstuff with some parts such as the stem having a very low nutritive value, while other parts such as the leaf are moderately well digested. This is also true of the chemical

composition and rumen degradability of these components. The relative proportions, and nitrogen contents of whole straw and its morphological components measured by a series of workers are summarised in Table 18. The oat straws had the highest crude protein content followed by wheat and barley respectively. In all cases, the leaf plus leaf sheath and the chaff had the highest concentration of nitrogen, with the stems having almost half the level of nitrogen. There were large differences in nitrogen content of leaves and stems between varieties of straw. It would seem appropriate, therefore, to mechanically separate the leaf and leaf sheath from the stem, to enable the former to be used as animal feed and the latter for industrial processing.

Ramanzin et al. (1986) also reported that the higher nitrogen content of the leaves and chaff compared with the stem was more readily degraded in the rumen.

7.4 Effect of agronomic/harvesting practice

There have been very few studies on the effect of agronomic/harvesting practices on protein value of cereal straws. Gately (1976) found that the crude protein content of barley straw increased directly with nitrogen fertiliser application rate. This was also shown by Kernan et al. (1984) with wheat straw. It was suggested that fertiliser levels selected to optimise grain yield would increase crop residue crude protein content and yield. It is thought that varieties of cereal which have high nitrogen translocation percentages (grain nitrogen:total plant nitrogen) will tend to have a lower nitrogen content of the crop residue.

Table 18. Proportions of botanical fractions of cereal straws and their nitrogen content (g kg^{-1} DM).

Botanical fraction			
Name	Proportion	Nitrogen content	Reference
Barley straw			
Whole straw	1.00	4.8	
Leaf blade	0.13	8.1	
Leaf sheath	0.31	3.7	Bhargava et al. (1988)
Stems	0.50	3.3	
Chaff	0.06	7.0	
Whole straw	1.00	5.7	
Leaves	0.45	7.0	
Internodes	0.44	4.1	Ramanzin et al. (1986)
Nodes	0.06	7.2	
Chaff	0.05	6.0	
Oat straw			
Whole straw	1.00	6.6	
Leaf+leaf sheath	0.31	8.3	
Internodes	0.57	4.5	Shand et al. (1988)
Nodes	0.07	-	
Chaff	0.05	-	
Wheat straw			
Whole straw	1.00	6.0	
Leaf+leaf sheath	0.34	6.7	
Internodes	0.46	5.0	Shand et al. (1988)
Nodes	0.06	-	
Chaff	0.14	-	

8.0 RECOMMENDATIONS FOR RESEARCH

The following areas have been identified as requiring further research. They have been prioritised as very high, high and moderately high.

Very high priority

i. Study the effects of geographical location, year, fertiliser application, fungal disease and cereal variety on nutritional quality of straws.

ii. Determine the relationships between the quality of straw stems and leaves and the possibilities for fractionation.

iii. Examine the role of plant breeding in influencing straw quality.

iv. Undertake a comparison of digestibility and rumen degradability measurements (in vivo and in vitro) for predicting straw intake and animal performance.

High priority

i. Undertake the development of in vitro and other laboratory methods for predicting degradability characteristics.

ii. Study the influence of selectivity of animals on straw and energy intake.

iii. Examine the influence of type of supplement on the intake and rumen digestion of straws and microbial protein synthesis.

Moderately high priority

i. Investigate the factors influencing the utilisation of nitrogen in ammonia/urea treated straws.

ii. Develop efficient and environmentally friendly means of upgrading straws, e.g., use of enzyme preparations.

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ACKNOWLEDGEMENTS

We wish to acknowledge the input into this review by Dr E. Owen (University of Reading) and Dr C. Lister and Mr T. D. A. Brigstocke (UKASTA). In addition, thanks are due to Mrs R. I. Hollyhead for her extensive input into the typing. For critically reading the manuscript we wish to thank Dr M. J. Griffin and Mr B. Bastiman.