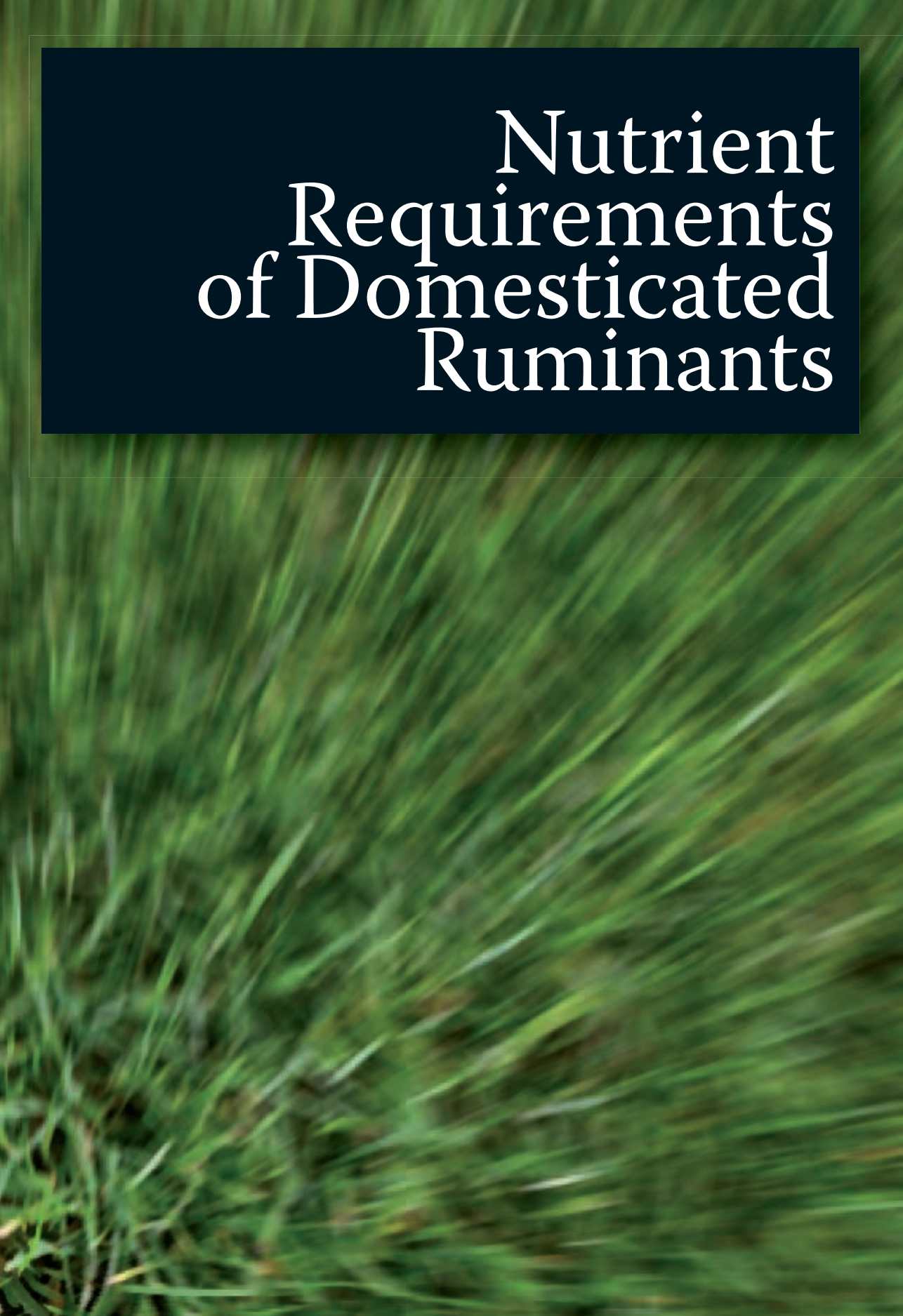
Nutrient Requirements of Domesticated Ruminants



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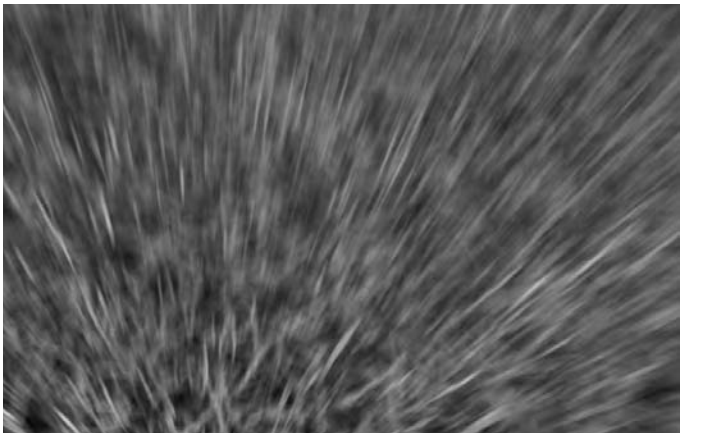

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General introduction

This publication represents a revision of the report entitled '*Feeding Standards for Australian Livestock. Ruminants*' that was issued in 1990 by CSIRO Publishing in conjunction with the Standing Committee on Agriculture. That report was produced in response to a resolution by the Standing Committee on Agriculture to establish an Animal Production Committee Working Party for the Introduction of Nationally Uniform Feeding Standards for Livestock (INUFSL). The Working Party, whose members are listed in the earlier report, established five subcommittees, one of which, with J.L. Corbett as Convenor, was instructed to prepare a report on the implementation of feeding systems for ruminants, based on metabolizable energy and to develop corresponding standards for protein.

In the 17 years since that report was published much new material on the nutrient requirements of ruminants has become available and the earlier publication is in need of revision. Although the Animal Production Committee no longer exists, a small editorial committee comprising M. Freer, H. Dove and J.V. Nolan, two of whom were members of the original subcommittee, has, with the agreement of CSIRO Publishing, attempted in this publication to bring the earlier report up to date.

Foreword to this edition

Despite major changes to some sections of the earlier report, this publication remains very largely the work of John Corbett, the Convenor of the Ruminants Subcommittee. The aims of this report are still those set out in his original Foreword, which is reprinted below. For several years he had been working towards the preparation of a revised edition but unfortunately died before this could be achieved. It has been left to the current editorial committee to complete this aim.

The changes that have been made to the earlier text stem partly from more recent research in ruminant nutrition and partly from experience in applying the earlier recommendations. In particular, use of the GrazFeed decision support tool (see Chapter 6), which was developed as a computer-based implementation of the subcommittee's recommendations for energy and protein requirements and for the prediction of feed intake, has over the years revealed a number of weaknesses in the earlier recommendations. The changes that have been made to GrazFeed to increase the accuracy of these estimates have now, in turn, been incorporated in the new recommendations for energy and protein.

In the title of this edition we have moved away from the concept of Feeding Standards towards recommendations on nutrient requirements. As John Corbett indicated in the original Foreword, there is a risk that the former term may be misunderstood as implying an inflexible measure of what animals ought to be fed. There is also some risk of confusion with Australian Standards as they are applied to such topics as animal feeds and animal health.

In addition to changes to the substance of the text, we have provided the reader with easy access to spreadsheet programs that allow rapid application of the recommendations on energy, protein and some of the major minerals to specific types of animal. We believe that this is more useful than loading the text with large tables that can cover only a small proportion of the possible instances. This report also includes a comprehensive index.

I thank my co-editors for their work in coordinating this revision. Drafts for each chapter were prepared and submitted for refereeing and amendment by readers appropriate for each topic and we are sincerely grateful for their contributions to this report. In particular, G.J. Judson and J.H. Ternouth made major contributions to the revision of Chapter 3.

M. Freer
Principal editor

Foreword to *Feeding Standards for Australian Livestock: Ruminants*

The Working Party on the Introduction of Nationally Uniform Feeding Standards for Livestock was instructed 'to implement feeding systems based on metabolizable energy', and 'to develop corresponding standards for protein' (Pryor 1980). It was understood that primary reference bases for ruminants were to be the Technical Bulletin of the UK Ministry of Agriculture, Fisheries and Food on *Energy Allowances and Feeding Systems for Ruminants* (MAFF 1975) and its antecedent, a Technical Review of the Agricultural Research Council (ARC 1965). The latter publication was undergoing extensive revision, and the ARC generously provided a pre-publication copy of the new edition (ARC 1980). Information on new developments made in other countries in feeding systems for ruminants also became available. The Ruminants Subcommittee is indebted to Dr Jarrige for providing copies of *Alimentation des Ruminants* (INRA 1978); Developments elsewhere in Europe were described in several publications, and in the USA the National Research Council has continued to publish revised editions of its reports on the Nutrient Requirements of Domestic Animals.

The Ruminants Subcommittee has gained much from correspondence and personal discussions with many who made major contributions to reports from the UK, Europe and the USA. We are most grateful to all who gave this help, which in a number of instances is identified in this Report as 'personal communication'.

The Subcommittee acknowledges the unstinted assistance it has received from numerous colleagues in Australia. Again their identities will be evident from references to personal communications as well as to their published work, and our thanks are due especially to those who have special knowledge of particular topics and have spent much time and effort in preparing appropriate sections.

The Subcommittee, of course, takes responsibility for the Report as a whole. It can be viewed as one of a family of reports on the feeding of ruminants, all of which have essentially the same knowledge bases but individually incorporate the knowledge into systems that reflect characteristics of the livestock industries in their countries of origin. Because the majority of Australia's ruminant livestock obtain most or all of their feed directly from pasture, particular attention has been paid to extending procedures for quantitative nutritional management to encompass grazing animals. For example, with a housed animal it is necessary to know what amounts of feeds with various qualities it can be expected to eat in order to formulate realistic rations for desired levels of production. The feed intake by a grazing animal is affected by a much larger number of variables including the quantity and spatial distribution of available herbage, and a procedure for predicting the quantity and quality of pasture intake has been developed (Chapter 6). Grazing incurs an energy cost, and the development of means for estimating its magnitude (Chapter 1) has conformed with a recommendation made at a conference on energy metabolism held at the Pennsylvania State College in 1935 that 'the net energy requirements of economic

maintenance be further investigated especially by the analysis of muscular activities incidental to maintenance as affected by individuality, age, sex, breed, species, and confinement or pasture' (NRC 1935). The introduction of an allowance for variation with feed intake in the estimation of the energy requirement for maintenance (Chapter 1), an 'overhead' cost that might better be termed the 'support metabolism', is also consistent with the concept from the Pennsylvania conference of 'economic maintenance'. Another innovation is the characterisation of the various breeds of animal and their sex type by a Standard Reference Weight. It is used as a basis for the prediction of the composition and energy content of liveweight gains (Chapter 1) and of the effect of growth promotants (Chapter 7); it is also used in the estimation of the change in liveweight equivalent to a unit change in condition score (Chapter 1), the net protein requirements for wool growth (Chapter 2), and in the prediction of feed intake (Chapter 6).

The feed available to many grazing animals in Australia is regularly of a much lower quality than is allowed for in other reports. Thus the consideration of protein nutrition (Chapter 2) includes guidelines for the use of protein and non-protein nitrogen supplements. Many animals are also subject to problems in the availability and quality of water supplies (Chapter 5), and inadequacies in their mineral nutrition are widespread (Chapter 3). An attempt has been made to define the nutrient requirements for wool production, a matter not considered in other than general terms in reports from other countries because wool is regarded more as a by-product of their sheep industries than, as in Australia, a product of prime importance.

Wool production is one of many topics where available information is inadequate. Similar difficulties in other reports have helped to focus attention on the experimental work that is needed, and it is expected that this Report will have a similar effect.

The term 'Feeding Standards' in the title of this Report should not be misunderstood. The purpose is not to determine inflexibly what an animal 'ought' to be fed. It is to facilitate the description in quantitative, and therefore monetary, terms of the responses of animals to their feed supplies and how changes in the supplies will affect animal performance. Some examples are given of the estimation of the energy and nutrients required for particular production, and of the production to be expected from predicted feed intakes. Extensive tabulation of requirements and predictions of performance for the wide variety of production systems and environments in Australia has not been attempted. It was the intention of the Working Party that this Report would be used by the State Departments in the preparation of publications that give information and advice appropriate for the systems of animal production that are their particular concerns. Moreover, the recommendations in this Report are cast in forms that are readily programmed, simplifying their use in both special and more general situations. Programs already exist (Chapter 7) and, as well as their use in practice, they facilitate what must be continuing tests of reliability and modifications of the recommendations.

I thank sincerely my colleagues in the Subcommittee for their innumerable major contributions that jointly have brought this work to a conclusion. Funds for travel were, unfortunately, not obtainable other than from our employing organisations. We are grateful to those who made available the funds that did allow meetings, intermittently of individuals and, rarely, as a group. The majority of the work was done by burdensome correspondence. However, such difficulties were of small moment compared with the professional and personal enjoyments from our collaboration.

J.L. Corbett
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Contents

Glossary

General	*(see below for terms used particularly in energy and protein nutrition)*
ADF	Acid detergent fibre
availability	That proportion of a stated concentration and amount of mineral in the diet, or of a particular mineral added in defined chemical form, that can be absorbed and utilised by the animal to meet its net requirement.
CF	Crude fibre
CS	Condition score
diet	The feed that is eaten by the animal. Synonymous with **feed** if selection by the animal does not occur.
digestibility	The intake of DM or a component (e.g. OM, CP), or its GE content, minus the amount in the corresponding faeces, expressed as a proportion of the intake (or as a percentage). General usage in this Report is synonymous with apparent digestibility, for which no allowance is made for endogenous material in the faeces (see **true digestibility**).
DM	Dry matter
DMD	Dry matter digestibility
DMI	Dry matter intake
DOM	Digestible organic matter
DOMD	The DOM in the feed (or diet) DM.
DOMI	Digestible organic matter intake
EBG	Empty bodyweight gain
EBW	Empty body weight (i.e. live weight minus the contents of the gastro-intestinal tract)
EE	Ether extract (crude fat); used to express the oil content of a feed or the fat content of the body
feed	That which is offered to the animal to consume, whether as pasture for grazing or as a feedstuff or mixture of feedstuffs. Synonymous with **diet** if selection by the animal is not possible.
FW	Live weight of the animal after a fast of specified duration (see FHP)
L	Level of feeding; the quantity of feed eaten by the animal expressed as a multiple of the amount sufficient for maintenance of zero ER, when L = 1
LWC	Liveweight change
LWG	Liveweight gain
maintenance	At the maintenance level of feeding, the requirements of the animal for nutrients for the continuity of vital processes within the body (including the

	replacement of obligatory losses in faeces and urine and from the skin) are exactly met so that the net gain or loss of tissue substances by the animal as a whole is zero. Maintenance is not synonymous with zero change in weight (see also under **Energy**).
MADF	Modified acid detergent fibre
MW	Metabolic weight; $W^{0.75}$
NDF	Neutral detergent fibre
OM	Organic matter
OMD	Organic matter digestibility
OMI	Organic matter intake
requirement	The amount of energy or any given nutrient that must be supplied in the diet to meet the needs of the animal.
SCFA	Short-chain fatty acids; synonymous with VFA
SRW	Standard Reference Weight; which, in concept, is the live weight of an animal (excluding fleece and conceptus) when skeletal development is complete and the condition score is in the middle of the range.
true digestibility	For this measure, account is taken of endogenous material in the faeces; only the amount of material of direct dietary origin in the faeces is compared with the amount in the feed (see **digestibility**). In this Report true digestibility is employed only in the recommendations for protein nutrition.
TSS	Total soluble salts in water
VFA	Steam-volatile fatty acids; synonymous with SCFA
W	Live weight less conceptus and fleece

Energy

BMR	Basal metabolic rate: heat production by a fasting animal in a postabsorptive state in a thermoneutral environment and at rest
DE	Digestible energy (MJ); synonymous with apparently digestible energy and calculated as the GE in the diet minus the GE in the corresponding faeces
DE_m	The DE required by the animal for maintenance
EB, ER	Energy balance or retention (equivalent terms); MEI – H
E_{cold}	The additional energy required by the animal in cold stress.
E_{graze}	The additional energy expenditure incurred by grazing compared with confined animals.
FHP	Fasting heat production: represents the minimum energy requirement for maintenance; BMR + energy for minimal activity
FM	Fasting metabolism: the FHP plus the GE of the urine excreted during its measurement (synonymous with fasting catabolism)
FMEI	The intake of rumen-fermentable ME, calculated by deducting the energy contents of ether extract and UDP from the MEI.
GE	Gross energy; synonymous with heat of combustion
H	Heat production by the animal
$k_{(subscript)}$	The net efficiency of use by the animal of ME (i.e. NE/ME) for energy maintenance(k_m), for NE retained as weight gain (k_g), as milk produced (k_l) and in wool (k_{wool}).

k_c	Measures the gross efficiency of use of ME for all energy costs incurred in the growth of the conceptus, because it includes the NE gain in the foetus and associated tissues and also the energy costs of their maintenance and of the enhancement of maternal metabolism.
maintenance	At the maintenance level of feeding (L = 1) the energy requirements of the animal are exactly met so that EB = 0; not synonymous with live weight maintenance. At other levels of feeding, this Report allows that there is variation in the energy requirement for the maintenance component of total energy expenditure.
M/D	Megajoules (MJ) of ME per kg of feed DM
ME	Metabolisable energy: the GE of the feed minus the GE of the corresponding faeces, urine and methane. At the maintenance level of feeding the heat production (H) by the animal exactly equals its ME intake; thus ME – H = ER = 0.
MEI	Metabolisable energy intake
ME_m	The ME required by the animal for maintenance
ME_p	The ME used by or available to the animal for production (i.e. = MEI – ME_m)
NE	Net energy. The NE value of a feed (MJ/kg DM) is the increase in the ER of the animal promoted by an increment in the intake of that feed. Although the energy value of any particular feed is standardly described by a single M/D value, its NE value varies with the purpose for which its ME is used, because of differences between the k_m, k_g and k_l values for that feed. The NE requirement of the animal for maintenance is equal to the amount of energy that would be lost from the body by tissue catabolism if the animal were fasted (see FHP, FM), and for production is the GE of gain in tissue mass and of milk produced.

Protein

ADIP	Acid detergent insoluble protein (the N present in ADF × 6.25)
CP	Crude protein, being total N × 6.25 (or × 6.38 for milk)
CPI	Crude protein intake
CPLS	Crude protein leaving the stomach through the pylorus to the duodenum; the (NAN × 6.25) in digesta in the form of MCP, plus UDP
dg	Degradability of CP estimated *in sacco*
DPLS	Truly digested protein leaving the stomach; made up of 0.6 MCP plus DUDP
DUDP	Truly digested UDP
Edg	The proportion of the CPI degraded in the rumen at a specified rumen outflow rate, estimated from dg and fractional outflow rate
EFP	Endogenous faecal protein (N × 6.25)
EUP	Endogenous urinary protein (N × 6.25)
FOM	Fermented organic matter; the diet OM truly digested in the rumen
MCP	Microbial crude protein, being the (N × 6.25) incorporated in the microbial population in the rumen during its growth. It is assumed that of the MCP, 0.15 is in the form of nucleic acids and 0.25 is indigestible, leaving 0.6 as digestible true protein.
NAN	Non-ammonia nitrogen

NDIP	Neutral detergent insoluble protein
PLS	True protein leaving the stomach through the pylorus to the duodenum; equals 0.85 MCP plus UDP
RDP	Rumen degraded protein (= CPI × Edg); may be used by microbial population in the rumen to synthesize MCP
true digestibility	For this measure, account is taken of endogenous material in the faeces; only the amount of protein of direct dietary origin in the faeces is compared with the amount in the feed (see **digestibility**).
UDP	Undegraded dietary protein; equals CPI – RDP

Conversion factors

To convert:	*to:*	*multiply[A] by:*
pound (lb)	kilogram (kg)	0.454
ton	tonne (t)	1.016
kilogram	gram (g)	1 000
kilogram	milligram (mg)	1 000 000
gram	milligram	1 000
milligram	microgram (μg)	1 000
microgram	nanogram (ng)	1 000
nanomol (nmol)	picomol (pmol)	1 000
ppm	μg/g	1
ppm	mg/kg	1
g/kg	%	0.1
mg/kg	%	0.0001
ppm	%	0.0001
mg/g	%	0.1
g/kg	%	0.1
calorie	joule (J)	4.184
joule	calorie (cal)	0.239
joule	kilojoule (kJ)	0.001
kilojoule	megajoule (MJ)	0.001
megajoules	kilocalories (kcal)	239.0
megajoules/d	watts (W) [W = J/s]	11.57
watts	megajoules/d	0.0864
gallons	litres (l)	4.544
°F	°C	0.556 (after subtracting 32)
acre (ac)	hectare (ha)	0.405
lb/ac	kg/ha	1.121

[A]In each case, for the reverse conversion divide by the same factor.

Values at various live weights (W) of $W^{0.75}$

W	$W^{0.75}$	W	$W^{0.75}$	W	$W^{0.75}$
5	3.3	60	21.6	350	80.9
10	5.6	70	24.2	400	89.4
15	7.6	80	26.8	450	97.7
20	9.5	90	29.2	500	105.7
25	11.2	100	31.6	550	113.6
30	12.8	125	37.4	600	121.2
35	14.4	150	42.9	700	136.1
40	15.9	200	53.2	800	150.4
45	17.4	250	62.9	900	164.3
50	18.8	300	72.1	1000	177.8

Chapter 1

Energy

Summary

The primary measure of the energy value of feeds is the amount in megajoules (MJ) of metabolisable energy (ME) per kilogram of dry matter, which is designated M/D. The most generally useful methods of predicting M/D are from measurements of the digestibility of dry matter (DMD), or of the organic matter in the dry matter (DOMD), at the maintenance level of feeding.

In predicting the ME requirement for maintenance (ME_m), there is an allowance for change with feeding level. Alternative equations are adopted, depending on whether the function is used in the formulation of rations at a known level of production or is used in the prediction of animal performance when ME intake is known. These two equations also include terms that allow prediction of the additional energy costs incurred by grazing compared with housed animals, and by cold stress. The net efficiency of use of ME for maintenance (k_m) is predicted as a function of diet quality.

The net energy requirements of gestation in sheep and cattle are estimated from functions based on those adopted by ARC (1980) and it is assumed that ME is used with an efficiency of 0.133 in meeting these requirements.

For immature animals, the energy, fat and protein contents of empty body gain are predicted with a family of equations that allow for variations in the composition of gain between species, breed, sex, stage of growth, and rate of gain. This is achieved mainly by expressing current live weight as a proportion of a Standard Reference Weight (SRW) assigned to each type of animal; with SRW defined as the animal's live weight when skeletal development is complete and its body condition is in the middle of the condition score range. For example the SRW is higher for Charolais than Hereford cattle, for Border Leicester than medium Merino sheep, and for entire male than for castrate animals that, in turn, have higher SRW than females of the same breed. The composition of empty bodyweight change in mature animals is predicted as a function of body condition. Multiplication of the predicted values for the composition of empty body gain by 0.92 converts these to a liveweight gain basis. The efficiency of ME use for gain (k_g) is not adjusted for feeding level, and is predicted with one equation for supplementary feeds and with another for grazed pasture, which accounts for a seasonal change in this efficiency.

Condition scores (CS) are defined. Relationships between change in CS and changes in live weight, body composition, production, and ME requirements are discussed. The gain or loss of body energy during lactation is related more closely to change in condition score than to change in live weight.

Tables give examples for cattle and sheep of estimates of the ME requirements for maintenance, liveweight gain and milk production but an unlimited range of estimates may be made from a spreadsheet program (ME Required) that is freely available from a website. The main equations used in making these predictions are listed in Appendix 1C. The same tables also predict performances of the animals when grazing pasture herbage of defined quality, the amounts grazed being predicted as described in Chapter 6.

Terminology

The unit of energy now used in many countries, including Australia, is the joule (J), which has superseded the calorie (cal):

$$1 \text{ cal} = 4.184 \text{ J}; 10^3 \text{ J} = 1 \text{ kilojoule (kJ)}; 10^6 \text{ J} = 1 \text{ megajoule (MJ)}$$

The watt (W) is often used in environmental physiology to describe the rate of heat loss or gain by an animal.

$$1 \text{ kW} = 1 \text{ kJ/s}$$

The heat production of, for example, a 300 kg cattle beast in a thermoneutral environment and fed for maintenance is about 0.45 kW (i.e. 39 MJ/d).

Descriptions of feed energy

Figure 1.1 illustrates how the gross energy (GE) of feed is partitioned in the ruminant animal. The loss of energy in the faeces (FE) may be 0.65 or more of the GE of very mature, senesced material, such as grain-crop stubbles and similar materials, but with feeds of the highest quality it may be 0.2 GE or even less.

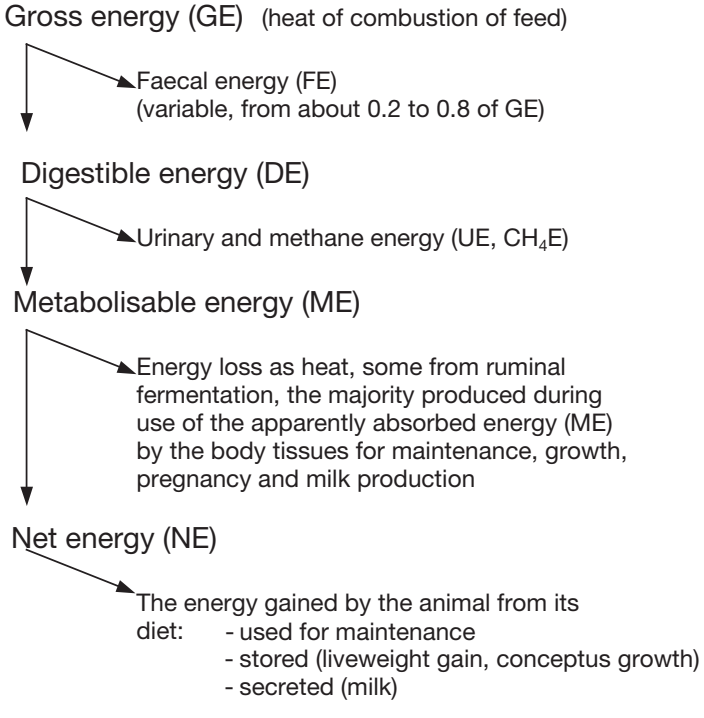

Fig. 1.1. Partition of feed energy in the animal.

The faeces contain substances of endogenous (i.e. body) as well as dietary origin so that (GE – FE)/GE describes the apparent digestibility of GE, but the terms digestibility (D) or digestible energy (DE) are generally used without qualification except when, rarely, the truly digestible coefficient is used which is: [GE – (FE – endogenous E)]/GE.

The primary description of the energy value of feeds and rations for animals is the metabolisable energy (ME) content. It is expressed in this Report, and by AFRC (1993), as MJ of ME per kg of dry matter (DM), symbolised as M/D.

$$ME = GE - (FE + UE + CH_4E) = DE - (UE + CH_4E) \quad (1.1)$$

where UE and CH_4E are the losses of energy in, respectively, urine and methane and on average together amount to about 0.19 DE (see p. 7). The principal source of methane is ruminal fermentation that also results in the production of heat equivalent to about 0.8 of CH_4E or around 0.06–0.08 of DE (Webster *et al.* 1975*b*). This heat helps to maintain body temperature in cold-stressed animals, but otherwise it is an energy loss not accounted for in the definition of ME.

The energy of the nutrients absorbed, defined as ME, is used by the tissues with an efficiency, k, of less than 1.0, resulting in the production of heat (H) that, as a proportion of ME, is (1.0 – k). The net energy (NE) gain by the animal and its energy balance (EB) is thus (ME – H).

EB can be negative. This situation occurs when the ME intake of the animal provides less energy than it must have in order to maintain homeothermy and vital processes in, and physical activities by, its body. Energy maintenance is defined as EB = 0, when the net gain or loss of energy from the tissues, as a whole, is zero. Consequently, when EB = 0, the ME intake of the animal exactly equals its heat production (ME = H).

The NE value of a feed, as distinct from the NE gained from any particular intake, is the change (Δ) in the energy balance of the animal resulting from a change in the amount of that feed eaten by the animal.

$$\text{NE value} = EB = \Delta ME - \Delta H \quad (1.2)$$

Its determination therefore requires the measurement of EB at two or more levels of intake, and the increment in NE gain resulting from an increment in the intake of the feed is commonly expressed as MJ per kg DM.

Utilisation of feed energy by the animal

No feed can be given a single NE value, no matter how this is expressed (e.g. NE/kg DM, NE/ME), because the value varies with the purpose for which ME is used by the animal. As shown in Fig. 1.2, ME is used with greatest efficiency for maintenance (k_m,), and with lesser efficiencies for growth and fattening (k_g), and lactation (k_l). The solid lines illustrating the various efficiencies are drawn for diets with M/D = 10 approximately.

The minimal energy requirement of an animal is its expenditure during fasting (see p. 14) when the energy it must have is supplied wholly by catabolism of body tissues. For each 1 MJ of ME then supplied by feed with M/D = 10, body tissues that would supply 0.7 MJ of NE are spared from use (k_m of diet = $NE_m/ME_m = 0.70$), and the ME intake that achieves energy equilibrium (zero retention or balance) is the requirement for maintenance (ME_m). With diet M/D greater or less than 10, the ME is used for maintenance with respectively greater (broken line a) or lesser (b) efficiency, as described on p. 20, and ME_m (MJ/d) is correspondingly less or more.

At higher intakes of feed with M/D = 10, the ME provided in excess of ME_m is used for weight gain with an efficiency (see p. 41) of about 0.4, which implies that each MJ so used results in the

synthesis of body tissue with a heat of combustion of 0.4 MJ and the production of 0.6 MJ heat. With lactating animals, ME is used for milk production with greater efficiency (see p. 47), and the value of k_l and that of k_g vary positively with M/D over the ranges indicated, approximately, by the vertical lines in Fig. 1.2.

Animal requirements

The energy value of each feed or diet is described by a single ME value (MJ/kg DM). The energy requirements of animals are also expressed in terms of ME (MJ/d).

To determine the ME requirements of animals it is necessary first to define the net energy requirements that comprise their expenditure for maintenance, plus the heats of combustion of liveweight gain, of the products of conception (NE_c), and of milk secreted:

$$\text{NE requirement} = NE_m + NE_g + NE_c + NE_l \quad (1.3)$$

The NE requirement for each function is then by divided by the appropriate k value to obtain the corresponding ME requirement:

$$\text{ME requirement} = NE_m/k_m + NE_g/k_g + NE_c/k_c + NE_l/k_l \quad (1.4)$$

It should be noted that the value for the use of ME for the products of conception k_c unlike k_m, k_g and k_l, is a gross efficiency and not a net efficiency (see *ME Requirements for Gestation*) because all the growth and maintenance costs of the conceptus are expressed as a function of gain in the conceptus.

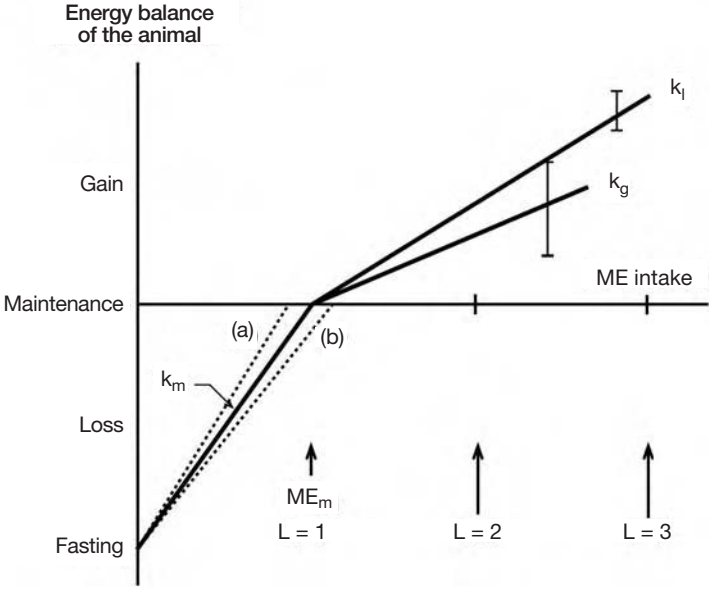

Fig. 1.2. Change in energy balance of the animal with, on the same scale, change in its metabolisable energy (ME) intake. ME_m is the ME intake that results in zero energy balance (maintenance); level of feeding (L) is unity. The solid lines showing the net efficiencies of use of ME (i.e. MJ net energy gain per MJ of ME) for maintenance (k_m), milk production (k_l), and growth and fattening (k_g) are for mixed diets providing 10 MJ of ME per kg dry matter (M/D = 10). With higher or lower M/D, the net efficiencies (NE/ME) are respectively higher or lower within the ranges indicated by the dotted lines (a) and (b) for k_m and the vertical bars for k_l and k_g.

Figure 1.2 follows the usual convention of illustrating the relationships between EB and ME intake as a set of straight lines. In reality, the relationships are curvilinear and show a diminishing returns effect (see p. 50). The AFRC (1993) make specific adjustments to the ME required by growing and lactating animals to allow for the curvilinearity. A different method of allowing for its effect has been adopted in this Report, as described on pp. 19 and 32.

Energy values of feeds

There are a very large number of equations for predicting energy values (e.g. Minson 1982*a*). In general, those given in this Report have been selected because they appear to be the most soundly based and because, amongst possible alternatives, they require the least number or least demanding of chemical or other analyses, but it should be understood that their reliability cannot be guaranteed. It is recommended that the reliability of the prediction equations be checked locally from digestibility and chemical measurements made on local feeds.

Unless otherwise indicated, the variables describing the properties of feed are quantities per kg of dry matter (e.g. MJ/kg DM; g/kg DM) and digestibility is in decimal form (e.g. 0.6 rather than 60%).

Gross energy (GE)

With most feeds eaten by domestic ruminants the GE value reflects that of carbohydrates such as cellulose (about 17.6 MJ/kg); it increases with increasing concentrations of protein (about 24 MJ/kg) and fat (about 39 MJ/kg), but decreases as its ash content rises, which may be due to either a change in the natural mineral content of the feed or to contamination with soil or other extraneous inorganic material. Michell (1974) reported a range of 18.2–20.1 (mean 19.0) MJ/kg DM for white clover, ryegrass and cocksfoot cut from Tasmanian pastures at various times throughout the year, and values for temperate pasture herbages in New Zealand (Hutton 1961) varied from 18.1–19.1 with a mean of 18.8 MJ/kg DM. The GE of a total of 60 samples of *Digitaria decumbens* (Pangola grass), *Sorghum almum*, and *Phaseolus atropurpureus* (Siratro), which represented various stages of growth, ranged from 17.2–18.7 (mean 18.0) MJ/kg DM (Minson and Milford 1966). Mean values in the report of the MAFF Standing Committee on Tables of Feed Composition (MAFF 1990) are in the range of 18.2 to 19.0 MJ/kg for various conserved forages (grasses and legumes as hays or artificially dried, grass silages and maize silages with DM contents determined by toluene distillation), and 18.4 to 18.9 MJ/kg for barley, wheat, maize and sorghum grains. Compared with those grains, oats tend to have higher EE (ether extract; crude fat) content (50 g/kg DM, or more) and GE often exceeds 19 MJ/kg DM (Nottle 1971; Margan *et al.* 1987); values for lupin are around 20 MJ/kg DM and whole cottonseed around 23 MJ/kg DM. Brassica (e.g. kale, turnips), potatoes and cassava have low EE contents (20 g/kg DM, or much less) and GE of around 17 MJ/kg DM.

A general value of 18.4 MJ/kg DM assumed by MAFF (1975, 1984*a*) is **adopted** in this report, although AFRC (1993) adopted a mean value for ruminant diets of 18.8 MJ/kg DM. Predicted values of k_m and k_l change by only 0.01 units if actual GE differs from that assumed by more than ± 1 MJ; there is no larger change in predicted k_g until actual GE differs by more than ± 0.5 MJ.

Digestibility and digestible energy (DE)

The most important single measure of the energy value of a feed is its digestibility determined *in vivo*; *in vitro* by incubation with rumen fluid (Tilley and Terry 1963) or with pepsin and

cellulase (McLeod and Minson 1978); or by near-infrared reflectance spectroscopy (NIRS) (Coleman and Henry 2002). All determinations by indirect methods must include samples of known *in vivo* digestibility as internal reference standards. As measured digestibility declines as feed intake increases, standard values must be obtained at a maintenance level of feeding.

Dry matter digestibility (DMD)

Determinations of DMD may be preferred to OM digestibility, which requires the ashing, and additional weighings, of samples.

$$\text{DMD} = (\text{Feed DM} - \text{Faeces DM})/\text{Feed DM} \quad (1.5)$$

Minson (1981*b*) reported that the standard error of a measurement *in vivo is* usually 1.0–1.3 DMD% units and that the mean RSD of equations to predict DMD% *in vivo* from *in vitro* measurements by the rumen fluid and cellulase procedures were ± 2.3 and ± 2.6 units, respectively.

Values for DE content as a function of digestible DM reported by Moir (1961), Minson and Milford (1966) and Michell (1974) varied from less than 17 to about 19 MJ/kg. A value of 18.4 MJ/kg digestible DM is generally appropriate when DMD is 0.6 or greater, and 18.0 MJ/kg for lower DMD. M/D may be calculated from DMD with this information and with knowledge of ME/DE, but less cumbersome methods of conversion are given on p. 7.

Organic matter digestibility (OMD)

Determination of the digestibility of OM, the energy-yielding fraction of the feed, may be preferred to DMD under some circumstances and estimates of the intake of digestible organic matter are used in the prediction of microbial protein synthesis (see *Microbial Protein Yield in the Rumen*).

$$\text{OMD} = (\text{Feed OM} - \text{Faeces OM})/\text{Feed OM} \quad (1.6)$$

MAFF (1975) assumed that the DE content of 1 kg digestible organic matter (DOM) is 19 MJ. Morgan and Barber (1979) state that this value has a standard deviation of ± 0.5 MJ, and as with GE it will increase with increasing crude protein (CP = total N × 6.25) and EE contents. Values reported for various temperate pasture plants in Australia by Michell (1974) were 18.8–21.6 MJ/kg DOM and varied directly with CP contents of the plant dry matter (range 79–357 g/kg DM). This relationship had been observed by Kellaway (1969) who reported that MJ/kg DOM (range 17.2–20.9 in 20 samples of forages containing 46–298 g CP/kg DM) could be predicted from the CP content (X) with the expression (17.77 + 0.0088 X); the RSD was ± 0.755. From a study of 60 samples of tropical forages (21–203 g CP/kg DM) Minson and Milford (1966) reported that MJ/kg DOM (observed range 16.2–20.1) could be predicted with the expression [14.15 + 3.18 log (CP% in DOM + 10)]; the RSD was not given. It appears that the following equation 1.7 of Terry *et al.* (1974) is equally well applicable to all these feeds.

$$\text{MJ/kg DOM} = 17.33 + 0.0124\ \text{CP g/kg DM} \quad (1.7)$$

Digestible organic matter in dry matter (DOMD)

The digestible organic matter content of feed dry matter (DOMD; Minson *et al.* 1960) is a most useful index of M/D, particularly if the feed is contaminated with soil. For convenience in application (see equations 1.11 and 1.12) it is usually expressed as a percentage:

$$\text{DOMD\%} = 100 \times (\text{Feed OM} - \text{Faeces OM})/\text{Feed DM} \quad (1.8)$$

The earlier edition of this Report listed a number of relationships between DMD, OMD, DOMD and M/D, which were based to a large extent on data from *in vitro* estimates of digestibility and predictions of M/D from chemical composition. The publication of newer tables by MAFF (1990) has provided a substantial database of digestibility and metabolisability values measured *in vivo*, from which more reliable relationships have been calculated.

Within 53 types of roughage feeds taken from MAFF (1990), including fresh grass and legume herbage, dried grass, hay, fodder crops, treated and untreated straw and silage, with DMD (%) ranging from 87% to 43%, the following regressions were calculated and are **adopted** in this Report.

$$\text{OMD} = 1.017\ \text{DMD} + 1.90 \qquad R^2 = 0.98 \text{ s.e.} = 1.69 \qquad (1.9A)$$

$$\text{DOMD} = 0.840\ \text{DMD} + 7.32 \qquad R^2 = 0.93 \text{ s.e.} = 2.52 \qquad (1.9B)$$

Within 40 'energy and protein feeds' taken from the same tables, including cereal and legume grains, extracted oil-seed meals and other by-products, with DMD ranging from 92% to 17% and EE ranging from 21% to 0.3%, the corresponding relationships were calculated.

$$\text{OMD} = 1.000\ \text{DMD} + 3.973 \qquad R^2 = 0.95 \text{ s.e.} = 3.48 \qquad (1.9C)$$

$$\text{DOMD} = 0.961\ \text{DMD} + 2.109 \qquad R^2 = 0.96 \text{ s.e.} = 2.74 \qquad (1.9D)$$

Metabolisable energy (ME, M/D)

Relationship with DE

It is generally accepted that on average:

$$ME_m = 0.81\ DE_m \qquad (1.10)$$

This relationship implies that the losses of energy in urine and methane are 19% of DE (Fig. 1.1). It has been adopted for general use by MAFF (1975, 1984*a*). There is considerable deviation from the mean value of 0.81 between feeds and AFRC (1993) cites a range of 0.81 to 0.86. MAFF (1990) reported values for 540 samples of grass, fresh or as hay or silage with a mean of 0.81 ± 0.03 (s.d.). Cereal grains have higher values: barley and oats 0.85 ± 0.02 and wheat 0.86 ± 0.02. The limited amount of information on tropical forages indicates the factor 0.81 can be used for those feeds.

It is concluded that 0.81 can generally be used, but 0.85 is probably more appropriate for cereal grains. Errors in ME so calculated are likely to be small relative to those that will probably occur in defining the digestibilitv of the feed being eaten by animals. For example there will inevitably be uncertainty about digestibility values predicted for pasture intake, or determined for a sample of hay or other forages taken from a large store of such feeds.

Prediction of M/D from DMD, OMD and DOMD

The earlier edition of this Report listed a number of prediction equations for M/D, but as discussed above, better data from *in vivo* measurements are now available from MAFF (1990). As suggested by Thomas (1990), the prediction of M/D from the digestibility of concentrate feeds is markedly improved by including ether extract (EE%) as a second independent variable. The data for the same 40 'energy and protein feeds' yield the following equations, which are **adopted** here.

$$\text{M/D} = 0.134\ \text{DMD} + 0.235\ \text{EE} + 1.23 \qquad R^2 = 0.95 \text{ s.e.} = 0.481 \qquad (1.11A)$$

$$M/D = 0.128\ OMD + 0.248\ EE + 1.06 \qquad R^2 = 0.92\ s.e. = 0.599 \qquad (1.11B)$$

$$M/D = 0.138\ DOMD + 0.272\ EE + 0.86 \qquad R^2 = 0.95\ s.e. = 0.478 \qquad (1.11C)$$

When M/D was related to DMD alone, the proportion of the variance accounted for decreased from 0.95 to 0.74 and the s.e. increased to ± 1.10.

In roughage feeds, EE is usually in the range 1–2%; only occasionally as high as 5%, and its inclusion in the regressions added nothing to the precision. Prediction from digestibility alone, using mean data for 53 roughages summarised by MAFF (1990), is more precise than from composite equations based on all 80 feeds, yielding the following equations, which are **adopted** here.

$$M/D = 0.172\ DMD - 1.707 \qquad R^2 = 0.93\ s.e. = 0.527 \qquad (1.12A)$$

$$M/D = 0.169\ OMD - 1.986 \qquad R^2 = 0.94\ s.e. = 0.474 \qquad (1.12B)$$

$$M/D = 0.194\ DOMD - 2.577 \qquad R^2 = 0.93\ s.e. = 0.519 \qquad (1.12C)$$

This database includes values for only 14 silages, which considered alone, yield the following equation:

$$M/D = 0.171\ DOMD - 1.368 \qquad R^2 = 0.77\ s.e. = 0.732 \qquad (1.12D)$$

Alternatively, the following equation is recommended by AFRC (1993):

$$M/D = 0.16\ DOMD \qquad (1.12E)$$

Before using any equations for silage feeds, it is essential that all analyses based on oven-dried material be corrected for the loss of volatile components, as discussed on p. 9.

Table 1.1. Values for organic matter digestibility (OMD%), digestibility of organic matter in the dry matter (DOMD%) and metabolisable energy, MJ per kg feed dry matter (M/D), predicted from dry matter digestibility (DMD%) with equations 1.9 and 1.11, for energy and protein feeds and for roughages, respectively

Energy and protein feeds					Roughages			
DMD[A]	OMD	DOMD[B]	M/D[C]	M/D[D]	DMD	OMD	DOMD	M/D
30	34	31	5.8	6.9	30	32	33	3.5
35	39	36	6.4	7.6	35	37	37	4.3
40	44	41	7.1	8.3	40	43	41	5.2
45	49	45	7.8	8.9	45	48	45	6.0
50	54	50	8.4	9.6	50	53	49	6.9
55	59	55	9.1	10.3	55	58	54	7.8
60	64	60	9.8	10.9	60	63	58	8.6
65	69	65	10.4	11.6	65	68	62	9.5
70	74	69	11.1	12.3	70	73	66	10.3
75	79	74	11.8	13.0	75	78	70	11.2
80	84	79	12.5	13.6	80	83	75	12.1

[A] Digestibility values are rounded to whole numbers.
[B] The relationship between OMD and DOMD is an approximation for feeds with ash contents not outside the range of 90 to 120 g ash/kg DM.
[C] With 2% EE.
[D] With 7% EE.

When these prediction equations are used with estimates of digestibility obtained *in vitro* or by NIRS, it is again emphasised that standard reference samples with a range of known *in vivo* digestibilities (at a maintenance level of feeding) should be included each time these determinations are made. Discrepancies between the known values and those observed, described with a

regression equation, are used to adjust the digestibility estimates of the other samples.

The M/D values approximately equivalent to a range of digestibility values are shown in Table 1.1. With cereal straws and other low quality roughages fed alone to animals in long or chopped form, actual M/D may be less than indicated by digestibility values if these have been determined *in vitro*. This is because such materials are usually ground before analysis and are likely to be fermented more readily and completely than in the rumen of the animal. *In vitro* digestion may also be promoted with added nitrogen (urea) and minerals, but inadequacies of such nutrients in practical feeding will reduce digestion *in vivo*.

Prediction of M/D from feed composition

Chemical analyses are often simpler than the determination of digestibility *in vivo*, but M/D has a larger error if predicted in this way. An equation used to predict M/D for a particular feed should have been derived from analyses of feeds of only that type. It is also necessary to derive a separate equation for, and apply it only to, each closely restricted range of feed when analyses are made by NIRS (Minson *et al.* 1983; Flinn and Murray 1987; Coleman and Henry 2002). With progressive improvement in calibration, NIRS is now being used to monitor quality in commercial feedstuff mills, and is being adopted by advisory services.

Forages. For the same roughages taken from MAFF (1990) (*Relationship with DE* above), including temperate plant material as fresh or dried herbage, hay, straw, silage and forage crops, the following equation was derived, similar to an earlier one by Barber *et al.* (1984):

$$\text{M/D} = 14.55 - 0.0155\ \text{MADF} \qquad \text{RSD} \pm 1.12 \qquad (1.13)$$

where MADF is modified acid detergent fibre (g/kg DM).

There appears to be no broadly based equation for tropical forages. For artificially dried *Digitaria spp.* Minson (1984) reported:

$$\text{M/D} = 16.654 - 0.024\ \text{ADF} \qquad \text{RSD} \pm 0.67 \qquad (1.14)$$

where ADF is acid detergent fibre (g/kg DM).

Compound Feeds. These feeds, in meal or pelleted form, may contain a wide variety of ingredients, including feeds of vegetable or marine origin with high protein and/or oil contents. The Rowett Research Institute (RRI 1981) reported a large number of relationships between composition and the measured M/D, and after further examination of the data the following equations were recommended for general use (Alderman 1985).

$$\text{M/D} = 11.78 + 0.0654\ \text{CP\%} + 0.0665\ \text{EE\%}^2 - (0.0414\ \text{EE\%} \times \text{CF\%}) - 0.118\ \text{Ash\%} \qquad \text{RSD} \pm 0.320 \qquad (1.15A)$$

$$\text{M/D} = 13.83 - 0.488\ \text{EE\%} + (0.0394\ \text{EE\%} \times \text{CP\%}) - (0.0085\text{MADF\%} \times \text{CP\%}) - 0.138\ \text{Ash\%} \qquad \text{RSD} \pm 0.264 \qquad (1.15B)$$

Correction of silage analyses

When silage is oven-dried, considerable amounts of volatile substances are lost, and observed GE (MJ/kg DM) values are higher than when DM is determined by a more accurate procedure. Until recently, this involved laborious toluene distillation but Kaiser *et al.* (1995) have shown that measurements by Karl Fischer titration are simple, rapid and more accurate. Their results with a range of pasture, maize and sorghum silages indicated that 'corrected dry matter' (CDM) could be predicted from oven dry matter (ODM, 80°C) by the following equation:

$$\text{CDM\%} = 3.96 + 0.94\ \text{ODM\%} \qquad \text{RSD} \pm 0.731 \qquad (1.16)$$

Concentrations of chemical constituents measured on oven-dried material should be corrected by multiplying by ODM/CDM. Digestibility values obtained on oven-dried material (e.g. ODMD%) can be corrected (CDMD%) by using the following equation (Barber *et al.* 1984):

$$CDMD = 100.0 - \left[\frac{(100 - ODMD)ODM}{CDM}\right] \qquad (1.17)$$

Table 1.2 shows CDMD values for silages of known ODM and ODMD.

Table 1.2. Values of corrected dry matter digestibility for silages of known oven dry matter (ODM%) and oven dry matter digestibility (ODMD%), predicted from equations 1.16 and 1.17

ODMD	ODM							
	15	20	25	30	35	40	45	50
50	59	56	55	53	53	52	51	51
55	63	61	59	58	57	57	56	56
60	67	65	64	63	62	62	61	61
65	71	69	68	67	67	66	66	66
70	75	74	73	72	72	71	71	71

Variation between grains

The M/D of cereal grains from various sources, not including Australia, were determined *in vivo* by MAFF (1990) and given the following mean values: wheat 13.7; oats 12.1; barley 13.3; sorghum 13.2; maize 13.8 (with s.d. of ± 0.5 to ± 1.0). Published values for Australian grains, based on *in vitro* determinations (AFIC 1987), generally lie within these ranges except for oats and sorghum, which show most variability.

With oats, variability in the energy value depends on the concentration of EE and the proportion of hull. The M/D is likely to be low when, owing to moisture stress in the plant near harvest, the grain has a high proportion of hull that is of very low digestibility (Crosbie and Rowe 1988). Variation between cultivars in the lignin content of hull affects digestibility of the whole grain (Rowe and Crosbie 1988). In addition, the CP in many cultivars is low, 90 g/kg DM or less, and the intake and performance of animals may then respond to supplementary N (Hodge *et al.* 1981; Butler and McDonald 1986). Digestibilities determined by Hodge *et al.* (1982), which are similar to several other Australian values, indicated M/D of 9.6–10.6, but the M/D measured by Margan *et al.* (1987) were 13.3 for the cultivar Coolabah (100 g CP/kg DM) and 13.6 for the cultivar Cooba (140 g CP/kg DM). Apart from the relatively high oil content of oats, methane energy losses were low so that ME/DE were 0.90 and 0.83 respectively. The DE measured by Rowe and Crosbie (1988) for two cultivars differing in lignin content were 14.0 (higher lignin) and 15.6 MJ/kg DM, which indicate M/D of about 12.0–13.7. With sorghum, M/D is cultivar dependent and may be lower than 10 MJ/kg DM (S. McLennan pers. comm.)

In drought feeding, the recommendation of the NSW Department of Agriculture (Freer *et al.* 1977; Clark 1980) that the ME of all cereal grains is to be taken as 12 MJ/kg as fed (10% moisture assumed) is supported by the work of Nottle (1971). However, when animals are given oats in circumstances other than drought feeding, account should be taken of the variability in its M/D.

Generally, there appears to be negligible loss of whole grain in the faeces of sheep, although, with ewes, Vipond *et al.* (1985) found losses of 12% and 5%, respectively, when whole barley or oats were fed with silage; but not with hay. However, when cattle are fed whole grain that has not been treated with alkali (Ørskov 1979; Sriskandarajah *et al.* 1980; Low and Kellaway 1983) nor cracked (rolled or coarsely milled), they may excrete substantial amounts. Some may be reingested by coprophagy, which probably accounted for the small difference in performance observed by Southcott and McClymont (1960) between drought-fed cattle given whole wheat and those given crushed wheat, but any excretion, in effect, reduces M/D. The loss appears to be less when cattle are given whole grain as the sole feed than when they are also given roughage, which appears to effect a reduction in the time the grain is retained in the rumen. Thus Ørskov (1980) reported the digestibility by cattle of whole maize as the sole diet may be about 0.8, but when given as a supplement to roughage diets it could be less than 0.5. When wheat was given alone to steers, Low and Kellaway (1983) found 12% was lost in faeces; Morris (1960) found that steers fed whole sorghum alone excreted 15% of this grain, but none was excreted by sheep. In contrast, Toland (1976, 1978) and Kimberley (1976) found that when whole grain was fed to cattle in rations containing 33% of hay, the proportion of grain voided was 20–40% for wheat, nearly 50% for barley but only 7–13% for oats.

Milk and milk substitutes

Equations to predict the GE of cow, ewe and goat milks are given on p. 47, and ME = 0.95 GE (Blaxter 1952).

Roy (1980) quotes an equation from the Netherlands that predicts the GE of air-dried milk substitute powders used for calf raising. Assuming 90% DM, GE (MJ/kg DM) is calculated as (0.22 fat g/kg + 0.006 protein g/kg + 13.033). When the powder is mainly dried milk, Roy (1980) suggests that ME = 0.91 GE, but metabolisability will decrease as its composition deviates from that of whole milk.

Fodder trees and shrubs (browse)

Descriptions of fodder trees and shrubs and information on their geographical distribution and capacity for regeneration have been given by Anon. (1951, 1952, 1958). Much of the information on their composition and digestibility has been obtained in Queensland (Harvey 1952*a*; Newman 1969; McLeod 1973; Newman and McLeod 1973), and McDonald and Ternouth (1979) give results for 70 samples. There is sufficient consistency with results for NSW browse (Wilkins 1966; Norton *et al.* 1972; Wilson and Harrington 1984) to make the generalisation that OM digestibility *in vivo* is around 0.40, but around 0.35 if the material is 'twiggy' and 0.45 if composed of fresh leaves, indicating M/D in the range of 4–6. The digestibility of some species is 0.6 or more (M/D = 8+). These include *Acacia aneura* (mulga) (O'Reagain and McMeniman 2002), *Eremophila spp.* (native fuchsias), *Acacia fernesiana* (mimosa bush), *Canthium oleifolium* (myrtle tree), *Santalum lanceoletum* (plumwood) (McDonald and Ternouth 1979), *Atriplex spp.* (saltbush) and *Kochia* spp. (bluebush) (Wilson 1966*a*), *Chamaecytisus palmensis* (tagasaste) and various tropical browse legumes (Bamualim *et al.* 1980). The digestibility of young green pine needles is about 0.36 (Anderson 1985) and even less, about 0.30, for older growths.

Variation in M/D

Effect of grinding

The digestibility *in vivo* of a forage is lower when it is ground than when in long or chopped form, but the practical consequences are probably small. Any reduction in M/D is at least counterbalanced by an increase in the net efficiency of use of the ME for growth and fattening (Greenhalgh and Wainman 1972) and, probably, for lactation (Campling and Milne 1972).

Level of feeding

Although, in general, the digestibility of a feed decreases with increasing level of intake, the reduction in DE is compensated to a variable extent by a reduction in the proportion of GE lost as urine and methane (ARC 1980); consequently, variation in ME/GE is much smaller than in DE/GE (Graham 1969*b*, 1983; Reid *et al.* 1980). In the definitions of the ME requirements of animals in this Report, no adjustments are made to allow for any variation that might occur with variation in intake.

On the other hand, as explained on p. 19, it has been accepted that the maintenance metabolism varies directly with feed intake, and the allowance for this effect on maintenance requirement that has been made is a 10% increment on the ME requirement for production, or 9% of the total ME intake (with an appropriate change to the coefficient on metabolic weight; see equations 1.19 and 1.20).

Associative effects of feeds

It is generally assumed that the ME provided by a mixed diet is simply the sum of the ME provided by each component of the diet, and that diet M/D is the mean of the individual component M/D weighted for the contribution that each makes to the mixture. These assumptions are made for 'nutritively complete' diets (Forbes *et al.* 1933). If single feeds that are unsuitable for ruminants owing to inadequate contents of N or other nutrients are a large proportion of a mixed diet, then diet M/D and other qualities may be less than expectation because contributions made by the other components, in themselves nutritionally adequate, have been diluted by the poor component.

The assumptions have generally been found to be true in the calorimetric studies at the RRI (1975, 1978, 1984), though some differences have been found between the M/D determined for wheat offals, sugar beet by-products, and sorghum grain when these were fed to sheep with silages, and the M/D for these feeds determined when fed with hay or dried grass (RRI 1978). These differences were not explained; with sorghum they would not have been caused by loss of grain in the sheep faeces.

It has long been known that the supplementation of roughages with feeds containing readily fermentable carbohydrate can result in a reduction in the digestibility of the roughage, and there may be a similar effect when grain supplements are fed to animals eating highly (0.8) digestible pasture (Milne *et al.* 1981). Mould *et al.* (1983*a*, 1983*b*) found that a major cause is rapid fermentation of the supplementary carbohydrate that results in a reduction in ruminal pH to a value approaching 6.0 and that consequently inhibits bacterial cellulolytic activity. Mould *et al.* (1983*b*) found that when a hay was ground and fed with rolled barley, contributing two-thirds of diet DM, the hay DM digestibility could be reduced by as much as 0.2 units (from 0.51–0.31) and the digestibility of the whole diet reduced by about 0.09. The reduction in hay digestibility

was less when it was given in chopped form, about 0.15 units, and when the barley was whole rather than rolled the reductions were about 0.12 for ground hay and about 0.05 for chopped hay. Dixon and Stockdale (1999) have reviewed the topic and suggested ways in which negative associative effects may be alleviated.

Reductions in digestibility from associative effects may not result in a corresponding reduction in energy value. There appears to be no direct evidence on this matter, nor information that would allow quantitative definition of associative effects. It can only be recommended that an associative effect be borne in mind as a possible source of error in ration formulation and the prediction of animal performance. It will, of course, be of particular importance with N supplementation of low CP forage (see p. 105).

Animal species

Many of the values for M/D that have been determined (e.g. MAFF 1990) or calculated from digestibilities, and the factors used to calculate M/D, have been derived with sheep but are generally used directly for cattle. Numerous studies, reviewed by Aerts *et al.* (1985), have shown that when DMD is about 0.66 or higher, values for DMD obtained with sheep tend to be greater than those from cattle. Conversely, cattle digest poorer quality feeds more than do sheep. For example, Poppi *et al.* (1981) found that the mean DMD for a forage was 0.54 with cattle and 0.51 with sheep at the equivalent level of feeding, and concluded that this was because cattle retained fibrous material in the rumen for a longer period. Goats also appear to digest fibrous feeds to a greater extent than sheep (Doyle and Egan 1980; Gihad *et al.* 1980). There have been very few studies in which ME were actually measured with both sheep and cattle and in these there was no significant difference between species (RRI 1975).

In the absence of any reliable alternative, M/D are to be used without alteration for sheep, cattle and goats. The most common consequence might be that M/D of roughages (DMD of 0.6 or less) would underestimate their energy value for cattle. It should be noted, however, that there will always be uncertainty about the accuracy of the M/D assigned to a feed, and that the coefficient of variation of digestibilities measured with apparently similar animals given the same feed is about 2%.

Physiological state

Age. Feed digestibility appears to increase with age in sheep, but this effect has not been identified with cattle (Blaxter *et al.* 1966*a*; Graham 1980; Vermorel and Bickel 1980). Vermorel and Bickel (1980) concluded that because energy losses in methane and urine tend to be less at earlier ages, so that ME/DE is higher than in adults, ME values of feeds determined in adult sheep can be used to calculate rations for growing ruminants, at least for the same feeding level. Values of k_g, but not k_m may vary with age (see p. 41).

Reproduction. Compared with non-breeding cattle and sheep given the same feed, M/D may be lower in late pregnancy and in early lactation, because of an increased rate of outflow from and reduced residence time of digesta in the rumen (Lamberth 1969; Thompson *et al.* 1978; Weston 1979; Hodge *et al.* 1982; Gonzalez *et al.* 1985; Oddy 1985; Weston 1988). No method of allowing for such a reduction in M/D can be recommended, but the possibility of its occurrence should be borne in mind when establishing rations for and assessing the performance of breeding stock.

Cold and heat. Digestibility varies with prevailing ambient temperature. From an examination of numerous studies made with cattle and sheep in temperatures ranging from –11°C to 38°C, the NRC (1981*a*) suggested that when there was prolonged exposure of animals to temperatures different from 20°C, DM digestibility values decreased by 0.0016 for each 1°C lower than 20°C and increased to the same extent for each 1°C above 20°C; the indicated change in M/D about the same reference temperature was ± 0.11% per °C. This effect appeared to be of more importance for forage than for concentrate diets, and it might be advisable to allow for it in computer models particularly for a period following shearing when the thermal insulation of sheep is reduced (see p. 27). In practical feeding in Australian conditions, other problems (e.g. identification of the amount and digestibility of feed eaten, effect of high ambient temperature on intake) will overshadow any allowance that might be made (e.g. M/D = 10 at 20°C adjusted to 9.84 at 5°C or 10.16 at 35°C if these ambient temperatures are sustained).

Energy requirements of the animal

Measurement of maintenance requirements

An animal unavoidably expends energy to maintain homeothermy and vital processes in its body, and in physical activities including those associated with feeding. At the maintenance level of feeding these basal energy requirements are exactly met so that the energy balance (EB), the net gain or loss of energy from the tissues of the animal as a whole, is zero. The metabolisable energy maintenance requirement is expressed as ME_m, which is then used with a variable efficiency k_m (see below) to be expressed as net energy, NE_m, the difference being a measure of the heat losses. The system adopted in this Report follows the UK use of ME_m as the measure of maintenance whereas NE_m has been more often used in the USA. In all systems, the basal energy requirement for maintenance is expressed as a function of the 'metabolic weight' (MW) of the animal, i.e. $W^{0.75}$.

Energy maintenance is generally not coincident with the maintenance of either the protein or the fat in the body, and neither of these with constant live weight although this is a practical guide to the adequacy of an intended maintenance ration. At higher levels of feeding, the fraction of total ME intake that growing sheep and cattle must use to meet their basic energy demands will rarely be less than 0.4, even at maximum intake, and with lactating cows will be less than 0.4 only when milk yields are about 20 kg/d or more. Successful management of animals, whether for survival (or, at the other extreme, for high production) is thus crucially dependent on knowledge of their maintenance requirements.

Methods for measuring the energy requirements for maintenance, expressed as ME_m or NE_m, have been reviewed by Van Es (1972, 1980) and Corbett and Ball (2002) and can be grouped under three headings: feeding trials, comparative slaughter methods and calorimetry.

Feeding trials

Practical estimates of maintenance needs can be obtained from long-term feeding trials designed to measure the quantity of feed that will maintain constant body weight. As already noted the result will be an approximation to, rather than an exact measure of energy maintenance, and is subject to errors arising from the difficulty of weighing animals precisely, possible changes in the content of the digestive tract, and problems in defining exactly the total quantity

of feed digested during the period of the study. This method is clearly unsuitable for growing, pregnant and lactating animals, and provides estimates of maintenance requirements only in terms of amounts of the particular feeds used.

Attempts to improve these estimates have used the regression of DOMI on MW, weight change and milk production, the coefficient on MW (DOMI per unit MW) being taken to indicate the maintenance cost. However, the method is subject to correlation errors and errors in weight measurements.

Comparative slaughter methods

The regression method can be significantly improved to measure ME_m in growing animals by slaughtering animals at the end of a feeding period of at least three months, and comparing the mean energy content of the whole empty body with that of a sample group of animals slaughtered at the start of the period. From trials using a number of feeding levels at or above maintenance, EB is regressed on ME intake to give the equation EB = bME – a, from which ME_m may be estimated as a/b, with coefficient b as an estimate of k_g.

Webster *et al.* (1974) have adapted the regression method to determine the 'predicted basal metabolism' (F') of young cattle raised in commercial fashion, without the regular alternations in plane of nutrition or the severe interruptions to growth that are concomitant with determinations of maintenance from measurements of fasting metabolism. They measured by calorimetry the rates of energy gain (ER) by the cattle on a number of occasions as they grew from weaning to slaughter. ME intakes were measured, and the values for k_m, and k_g for the diets were also obtained by calorimetry. The F' calculated by substituting appropriate values in the expression $[k_m\ (MEI - ER/k_g)]$ were consistently higher than the values for heat production determined with fasted cattle.

Calorimetry

Measurements of the fasting metabolism (FM) of cattle and sheep are used by the ARC (1980), MAFF (1984*a*) and AFRC (1993) to define the energy requirements for maintenance. Fasting metabolism comprises the fasting heat production (FHP) measured by calorimetry plus the gross energy of the urine excreted during the same period and, on average, FM = 1.08 FHP.

The animals should be trained and accustomed to the calorimeter, and kept in a thermoneutral environment. The measurements are usually made during the third and fourth days after withdrawal of feed, but not water. By this time, the respiratory quotient should have decreased to about 0.70, and methane production should be no more than about 0.5 l/d from sheep and 2 l/d from cattle. Lines and Peirce (1931) and Marston (1948) found that FHP varied directly with the level of feeding of the animal before fast. There are numerous other similar reports. For this reason, feeding of animals during the three weeks before measurement has been standardised at approximately the maintenance level.

For practical use, the FM values have to be adjusted for the differences between the fasted weight (FW kg) of an animal and its live weight (W) when it is fed. The ARC (1980) assumes $FW^{0.75} = (W/\ 1.08)^{0.75}$ or $W^{0.75}/1.06$ for ruminant diets and $(W/\ 1.05)^{0.75}$ or $W^{0.75}/1.04$ for milk-fed young. The fed animal is also more physically active than when it is fasted, even though still confined, and to allow for the consequent increase in energy expenditure the ARC (1980) adjust FM by adding an 'activity allowance' of 0.0043 MJ/kg W for cattle and 0.0106 MJ/kg W for sheep.

Variation in fasting metabolism and ME requirements for maintenance

As judged by oxygen consumption of body tissue, about half of the maintenance energy needs are in the gut wall and liver for the absorption and metabolism of digested nutrients; skin, kidneys and nervous tissue account for about one-third and basic muscle activity for the remainder (Seal and Reynolds 1993). It follows that variation in the level of activity of these tissues due to genotype, age, physiological state, level of feeding and environmental conditions will modify the maintenance energy requirement of the animal.

Genotype

Studies by Frisch and Vercoe (1977, 1984) indicate that, in predicting ME_m, the appropriate coefficient on MW for *Bos taurus* cattle is 1.4× the coefficient for sheep, while that for *B. indicus* is 1.2×. Blaxter (1962) failed to find significant differences between sheep breeds, but large differences between individuals within breeds. Measured values of FM for sheep inevitably include the energy retained in the basal production of wool during fasting, but differences between breeds in this respect have a negligible effect on the total requirement. The large database reviewed by Sahlu *et al.* (2004) indicated that the function used to predict ME_m for sheep may also be used for goats, a view that agrees with the recommendation by AFRC (1998).

Age, gender and physiological state

Fasting metabolism decreases with age, at about 8% per year in the young animal, with the rate falling to zero at about six years of age (Blaxter 1962; Graham *et al.* 1974), by which time FM is about 0.84 of the initial value. FM is 15% higher in entire male animals than in females or castrates (Graham 1968; ARC 1980).

Graham *et al.* (1974) found that the FHP of lambs consuming milk alone was 23% higher than that of weaned lambs, the increase depending on the proportion of milk in the diet. Corbett *et al.* (1980) reported increases of 14% in ME_m in pregnant ewes after 130 days gestation; large increases during lactation are discussed below in relation to level of feeding.

Feeding level

As noted above, observed FM vary with the level of feeding before fast. When this is standardised at L = 1, a series of measurements made at intervals during a long period with animals accustomed to the procedure usually show high repeatability if allowance is made for change in age. The standard values for FM may consequently be viewed as defining the minimal net energy requirements for maintenance of animals that are to be fed for maintenance only, but they are used by the ARC (1980) and AFRC (1993) as an operational definition of the maintenance requirements of animals at all levels of feeding.

There is much direct and indirect evidence that the inescapable non-productive energy expenditures of animals, their notional maintenance requirements or 'support' metabolism, vary directly with their feed intake. The causes include changes in both the size of and rates of metabolism in organs and tissues (Armstrong and Blaxter 1984; Ferrell *et al.* 1986) with alterations in the rates and energy costs of blood flow, oxygen uptake by the liver (Ortigues and Durand 1995) and in the transfer of nutrients from the lumen of the gut (Seal and Reynolds 1993), protein turnover, sodium-potassium ion transport and other essential processes (Milligan and Summers 1986).

Graham (1982) has discussed variation in the notional maintenance requirement and has suggested that, because the response to change in feed intake is rather slow, the effect is not allowed time for full expression in short-term calorimetric studies in which the amount of feed given to animals is usually changed at intervals of about three weeks. Consequently, when animals in these studies are fed at production levels they will tend to use a smaller fraction of their ME intake for maintenance, and will have a greater amount of ME available for production, than when the same intake is sustained over longer periods as with animals in comparative slaughter trials (CST). Values for k_m obtained by CST with cattle (e.g. Garrett 1980) and sheep (e.g. Thomson *et al.* 1979) are generally less than those obtained for similar feeds by calorimetric measurements of energy balance (e.g. ARC 1980). Consequently the energy gain by animals in CST from a given intake of a feed is generally found to be less, and the derived estimates of ME allowances for a given liveweight gain tend to be greater, than the gain and allowances determined calorimetrically.

Further evidence that non-productive energy expenditures are greater in animals fed for production rather than for maintenance is provided by Andersen (1980). From regression analyses of the feed intakes, daily gains and data obtained at slaughter of several hundred cattle of various breeds, he concluded that an important variation in maintenance requirements ('weight-dependent use of non-productive energy') exists between feeding levels. His conclusion is consistent with the calorimetric evidence from Lines and Peirce (1931), Marston (1948), and others, of an increase in basal energy expenditure, measured as FHP, with increasing feed intake before fast. It is also consistent with the proposition of Webster (1978) that, in essence, his values for 'predicted basal metabolism' (see p. 15) provide a more realistic definition of the notional maintenance requirements of growing cattle than do the lower estimates of these requirements derived from measurement of FM.

Table 1.3. Values for the net energy requirements for maintenance (NE_m MJ/d) of 35 kg sheep and 300 kg cattle, penned, from several energy feeding systems and estimated from survival (drought) feeding trials

Type of animal	NE_m MJ/d	Source
Sheep		
Breeding ewes, growing ewes and wethers (average)	3.6	ARC (1980)
All types (average)	3.5	MAFF (1984)
Adult	4.3	NRC (1975)
Adult, non-breeding, drought-fed	3.2	CSIRO (1958)
Cattle		
Lactating cows, heifers, steers	24.3	ARC (1980)
All types	25.5	MAFF (1984)
All types	23.3	NRC (1984)
Growing	23.8	Van Es (1978)
Steers and heifers, drought-fed	20.3	Morris (1968)

There is also much evidence of the corollary that maintenance requirements per unit metabolic weight decrease when animals are undernourished. It is known that the basal metabolic rate of non-ruminants, including man, decreases during periods of inanition (e.g. Keys *et al.* 1950), and in these circumstances there is also a decrease in the FHP of cattle (Benedict and Ritzman 1923) and sheep (Marston 1948; Farrell *et al.*1972; Graham and Searle 1979; Thomsen *et al.* 1980). Foot and

Tulloh (1977) and Ledger and Sayers (1977) restricted the feed intakes of steers so that they were held at constant W for periods of up to 24 weeks. The initial allowances of feed had to be reduced from 18 to as much as 52% to hold W constant, and though steers in the former trial might not have been at energy maintenance, Foot and Tulloh (1977) showed that there had been little change in the composition of the bodies of their steers during the 120 day period of their trial.

Further evidence of reduced maintenance requirement is provided by drought feeding trials with sheep fed wheat or wheat plus roughage by M. C. Franklin, G. L. McClymont, P. K. Briggs and colleagues at Glenfield, NSW, which have been summarised by CSIRO (1958), and with cattle fed grains with or without lucerne hay in Queensland, which have been summarised by Morris (1968). The results of these trials are shown in Table 1.3. To allow direct comparison with the other values for maintenance that are shown, the requirements have been given in terms of net energy. Morris (1968) estimated that maintenance was achieved with an intake of 481 kJ DE/kg $W^{0.75}$/d, equivalent to 390 kJ of ME, and to 281 kJ of NE assuming that average M/D of the feeds used was 11 and, from equation 1.21, k_m, was 0.72. The results from the sheep studies have been converted in a similar manner. The values for sheep from ARC (1980) and from MAFF (1984*a*) are means of the estimates for breeding ewes and growing sheep.

For sheep and cattle, the NE_m estimated from drought feeding trials are 84% and 90%, respectively, of means of the other four values. Drought feeding studies with cattle by Southcott and McClymont (1960) also indicated relatively low maintenance requirements. They found that 202 kg steers maintained W when given 1.6 kg wheat (air dry) daily, and if no whole grain was lost in faeces this is equivalent to $(1.6 \times 12 \times 0.74) = 14.2$ MJ of NE or, pro rata, 21.1 MJ for 300 kg W.

Operational definitions of ME requirements for maintenance

There is a progressive decrease in energy gain by the animal per unit increase in ME intake that (the ARC (1980) recognised) is not accounted for by a decrease in the metabolisability of the feed with increasing level of feeding (L). The ARC (1980) chose to regard this curvilinearity as being due to a decrease in the efficiency of utilisation of increments of ME above a constant maintenance, rather than to a constant efficiency (k_g) and a progressive increase in a component of total energy expenditure analogous to a maintenance cost.

Consequently, in the ARC system, maintenance is defined rigorously as the amount of feed that results in zero energy retention, estimated as FM/k_m, and in common with other energy feeding systems takes the value of ME_m per unit W for any particular class of animal as being immutable. The system allows for decreasing efficiency of ME use for growth and fattening, above a constant maintenance, by progressively discounting the overall efficiency of the use of ME as L increases, according to an exponential function of Blaxter (1974). In lactating animals, the total ME requirements are increased by a factor CL dependent on the feeding level.

The alternative to the ARC (1980) standpoint, **adopted** in this Report and corresponding to 'economic maintenance' (NRC 1935), is to allow for variation in non-productive energy expenditures and regard the balance of the ME intake that is available for production as being used with constant efficiency. While k_g would vary with M/D, the value for any particular feed would then be used without adjustment at all feeding levels.

An approach that is compatible with current concepts and the use of k_m k_g and so on, stems from studies by Graham *et al.* (1974). They found that the observed variation in the basal metabolic rate (BMR or, essentially, FHP) in sheep as they grew at various rates from one week to 27 months of age was described by the following equation:

$$BMR(MJ/d) = (1 + 0.23\ M)\ (0.257\ FW^{0.75} \exp(-0.08A) + 2.8\ G + 0.046\ DE) \quad (1.18)$$

where:

FW = fasted live weight (kg),

A = age in years (i.e. six months = 0.5),

G = growth rate, kg/d, during a period of several weeks before fasting,

DE = intake of digestible energy, MJ/d, immediately before fasting,

M = the fraction of the DE intake provided by milk.

The generalised equations set out in the following section were derived by Corbett *et al.* (1987*a*) from this function (see Appendix 1A).

The prediction of ME requirements for maintenance with generalised equations

The recommendations in this Report on energy requirements are based on:

(a) acceptance and definition, of variation in the maintenance (support) metabolism, the non-productive component of energy expenditure. The terms maintenance and ME_m will be used in this context;

(b) the consequent use of k_g without adjustment at any level of feed intake.

*The generalised equations **adopted** in this report*

To calculate ME in ration formulation:

$$ME_m\ (MJ/d) = K.S.M.(0.28W^{0.75} \exp(-0.03A))/k_m + 0.1ME_p + ME_{graze} + E_{cold} \quad (1.19)$$

To calculate ME when ME intake is known and animal performance is to be predicted (note change from 0.28–0.26 $MJ/W^{0.75}$ with change from ME_p to MEl):

$$ME_m(MJ/d) = K.S.M.(0.26W^{0.75} \exp(-0.03A)/k_m + 0.09MEI + ME_{graze} + E_{cold} \quad (1.20)$$

where:

K = 1.0 for sheep and goats, or 1.2 for *B. indicus*, or 1.4 for *B. taurus*, or intermediate values for crosses between these cattle types;

S = 1.0 for females and castrates and 1.15 for entire males (rams, goats, bulls);

M = 1 + (0.23× proportion of DE from milk);

W = live weight (kg), excluding conceptus and, for sheep, the fleece;

A = age in years, with a maximum value of 6.0, when exp(–0.03A) = 0.84;

k_m = net efficiency of use of ME for maintenance (see below for prediction);

ME_P = the amount of dietary ME (MJ) being used directly for production;

MEI = total ME intake (MJ);

ME_{graze} = additional energy expenditure (MJ) of a grazing compared with a similar housed animal, divided by k_m;

E_{cold} = additional energy expenditure (MJ) when the ambient temperature is below the animal's lower critical temperature (additional ME is used with an efficiency of 1.0 in cold stress).

For convenience where the proportion of milk in the diet is not known, M can be estimated from: M = 1 + (0.26 – B*a*), with B = 0.015 for suckled lambs and kid goats or 0.010 for suckled calves, and *a* is week of life (Langlands 1977; Doney *et al.* 1984). The minimum value of M is 1.0.

FM values in a thermoneutral environment (E_{cold} = 0) predicted with equation 1.19 are shown in Tables 1.4 and 1.5. They are generally similar to those predicted with the ARC (1980) equations, which were derived by comprehensive examination of FM measurements.

Prediction of k_m

The ARC (1980) equation to predict k_m has been derived from measurements of the efficiency with which dietary ME is used to spare body tissue from catabolism in animals fed at levels not exceeding maintenance (zero energy gain), and fasted. The equation must therefore be used only for converting basal energy expenditures, unaffected by enhancement of metabolism from higher feed intakes, into requirements expressed as ME. As shown in Appendix 1A, this constraint has been observed in the derivation of the generalised equations. The original term 0.046 DE for the prediction of BMR becomes 0.062 ME_m when FM is to be predicted for animals as though they had been at a maintenance level of feeding, and that original term was eliminated by this means.

It is therefore legitimate to use the ARC (1980) 'preferred' values for k_m in association with the generalised equations 1.19 and 1.20. These values, converted for M/D, for diets with an average GE content of 18.4 MJ/kg DM are **adopted** in this Report:

for milk diets (unweaned lambs, goats, calves): $k_m = 0.85$

for other diets (including the feed other than milk consumed by unweaned young):

$$k_m = 0.02\ M/D + 0.5 \qquad (1.21)$$

Table 1.4. Estimates of the fasting metabolism of female and castrate sheep (FM, kJ/kg$W^{0.75}$ per day) at various ages calculated with the generalised equation 1.19, and the 'preferred values' of ARC (1980); values increased by 15% for entire males

		FM = M(0.28$W^{0.75}$ exp(–0.03A))		ARC (1980)	
Age (years)		Unweaned[A]	Weaned	Table 3.14[B]	Adjusted[C]
0.02	(a=1)[A]	348	–		
0.1	(a=5)	331	279		
0.2	(a=10)	309	278	350[D]	358
0.3	(a=16)	283	277		
0.4	(a=21)	277	277		
0.5		–	276	260[E]	270
1.0		–	272	245	261
2.0		–	264	230	247
3.0		–	256	–	–
4.0		–	248	215	233
5.0		–	241	210	228
6.0		–	234		

[A] Values for unweaned sheep incremented with the factor M = 1 + (0.26 – 0.015a), where a = week of life.

[B] 'Preferred values' for FM, kJ/d per kg fasted live weight$^{0.75}$ (ARC Table 3.14).

[C] Values for minimal metabolism, equivalent to those predicted with equation 1.19. They are FM adjusted from a fasted to an unfasted live weight basis, and with the addition of the 'activity allowance' of 10.6 kJ/kg W per day which, per kg $W^{0.75}$, is approximately 20 kJ at W < 20 kg, 25 kJ at W = 30 kg, and 30 kJ at W > 40 kg.

[D] Value for 'unweaned, liquid diet'. Adjustment = $350/(1.05)^{0.75} + 20$.

[E] Adjustment for this and following values = $FM1(1.08)^{0.75}$ plus 25 or 30 kJ.

The validity of predictions when M/D is seven or less is uncertain, because data used to derive the equations did not include any measurements for such feeds. A k_m of 0.62 for a low quality roughage (M/D = 6) might, however, be a realistic index of its practical feeding value; for example, sheep given ground and pelleted cereal straw by Mulholland *et al.* (1974) lost more live weight than would be expected if $k_m = 0.7$ (MAFF 1975) was applied to their MEI. It would

generally be inadvisable to use fixed values for k_m such as the 0.72 and 0.70 used for cattle and sheep respectively by MAFF (1975, 1984*a*). In Australia, compared with the UK, variation in diet quality is of much greater practical importance, and fixed k_m could overestimate the worth of low quality roughages as maintenance feeds by 10% or more.

Table 1.5. Estimates of the fasting metabolism (FM) of weaned *Bos taurus* female and castrate cattle at various live weights (W) and ages (years) calculated with the generalised equation 1.19[AB], and of their minimal metabolism predicted with an equation of ARC (1980)[AC].

	Age (years)								
W(kg)	**0.2**	**0.4**	**0.6**	**0.8**	**1.0**	**2.0**	**4.0**	**6.0**	**ARC(1980)**
50	7.3	7.3	–	–	–	–	–	–	7.1
100	12.3	12.3	12.2	–	–	–	–	–	11.4
150	–	16.6	16.5	16.4	16.3	–	–	–	15.1
200	–	20.6	20.5	20.4	20.2	–	–	–	18.4
250	–	–	24.2	24.1	23.9	23.2	21.9	20.6	21.4
300	–	–	–	27.6	27.4	26.6	25.1	23.6	24.3
400	–	–	–	–	34.0	33.0	31.1	29.3	29.6
500	–	–	–	–	–	39.0	36.8	34.6	34.5
600	–	–	–	–		44.8	42.1	39.7	39.2

[A] Values increased by 15% for entire males (bulls).
[B] Values for unweaned calves increased by [I + (0.26 – 0.01a)], where a is week of life with a maximum value of 26.
[C] Minimal metabolism (MJ/d) = 0.53 $(W/1.08)^{0.67}$ + 0.0043W.

Graham (1980) found that k_m did not vary with age of animal, and Vermorel and Bickel (1980) came to a similar conclusion. Indirect evidence that it is higher in Brahman cross than in Afrikaner cross or Hereford × Shorthorn steers (Frisch and Vercoe 1976) has not been examined by direct measurement.

Use of energy from liveweight loss

Animals will intermittently experience periods of feed shortage, especially in a pastoral system of production, when they have to use energy from catabolism of body fat and protein for maintenance or survival. It is recommended (p. 40) that the energy content of 1 kg liveweight loss by non-lactating animals of any particular live weight should be taken to be the same as the energy content of 1 kg liveweight gain made at the same live weight by animals of the same breed and sex.

The energy from liveweight loss will not be used with 100% efficiency, but there is little information on its use for maintenance. Marston (1948) assessed the energy costs as 20% of total energy provided, that is, an efficiency of 0.8, and a similar value, 0.79, is implied in a report by Flatt *et al.* (1965); k_m (body energy) = 0.80 is **adopted**.

Energy expenditure at pasture (E_{graze})

Evidence is lacking on the efficiency with which ME is used for muscular work (Graham 1985) but, following ARC (1980), is taken to be the same as the efficiency of use for maintenance, k_m. It follows that the ME requirement for grazing (ME_{graze}) is E_{graze}/k_m.

Calorimetric studies have established the following energy costs of various physical activities by ruminant animals:

Activity	*Energy cost per kg W*
Standing (compared with lying)	10 kJ/d
Changing body position (double movement of lying down and standing again)	0.26 kJ
Walking (horizontal component)	2.6 kJ/km
Walking (vertical component)	28.0 kJ/km
Eating (i.e. prehension and chewing)	2.5 kJ/h
Ruminating	2.0 kJ/h

The first four values are the estimates made by the ARC (1980) from a review of determinations made by several workers. The energy cost of ruminating is that estimated for sheep by Graham (1964); his value for eating of 2.3 kJ/h per kg W is slightly less than the 2.5 kJ/h listed, which is the mean of numerous estimates reviewed by Osuji (1974). The mean value from studies by Adam *et al.* (1984) on cattle given various types of feed or with simulated grazing (Holmes *et al.* 1978) was 2.0 kJ/h (s.d. ± 0.4), and the energy cost of eating expressed in these terms showed only small variation among feeds. There is, however, considerable variation in the time taken to eat a given quantity of DM, and Adam *et al.* (1984) found that cattle expended about 0.23 kJ/kg W in eating 1 kg DM in the form of pelleted feeds, 1.03 kJ/kg W in eating 1 kg DM of hay or dried grass, either long or chopped, and 1.43 kJ/kg W in eating 1 kg DM (7.4 kg fresh weight) in chopped turnips. The expenditure in simulated grazing was 3.42 kJ/kg W per kg DM. The values for sheep in the studies they reviewed (kJ/kg W per kg DM eaten) were approximately 1.1 for pelleted feeds, 4.0–7.0 for long or chopped hay or dried grass or freshly cut forage, and 25.1 for simulated grazing (Graham 1964).

For animals given feed in stalls, pens, or yards, it can generally be assumed that $ME_{graze} = 0$. This is because ME_m already allows for the expenditure of energy on the physical activities (including standing, eating and ruminating) that are normal in these conditions. As noted on p. 15, the ARC (1980) increments FM with an allowance for the greater activity of fed compared with fasted animals. MAFF (1975, 1984*a*) make a similar type of allowance, which is also present in equations 1.19 and 1.20 because the coefficients, in the first term, of respectively 0.28 and 0.26 are rounded up (Appendix 1A). These increments do not account for the energy costs of eating and ruminating, but an allowance for these activities is inherent in the k_m, value used to convert NE_m to ME_m. The ME requirements for maintenance include the energy expenditures incurred in eating and ruminating the amount of feed required to achieve this state, and the value of k_m for the particular M/D is less than it would be if the ME could have been gained from the diet without those activities.

Some part of the decrease in k_m with decreasing M/D is caused by the increase in muscular work associated with the intake of progressively less digestible, more fibrous, feed. Similarly the varying values for k_g and k_l, which primarily reflect variation in the energy costs of the synthetic processes in production, also reflect the costs incurred in eating and ruminating the feed that ultimately provides the metabolites for the production.

Housed animals may have an above-average energy expenditure on eating if their ration includes a large proportion of long roughage, or involves self-feeding from a store of straw, hay or silage, but any allowance made should be small. For example, if the DM intake of a 300 kg steer was 3 kg from a pelleted feed plus 3 kg from hay then (Adam 1984) the energy expended in eating would be about 1.23 MJ of NE, or about 1.8 MJ of ME; if it ate 6 kg of hay DM the extra cost would be about 0.9 MJ of ME that is only 2%, approximately, of ME_m and equivalent to little more than 1% of the ME intake. Housed animals would not usually be required to walk so far to

feed or for milking that there was an important effect on their energy requirements (e.g. about 1.1 MJ of ME for a 300 kg animal for each 1 km walked in excess of normal distances).

The value of ME_{graze} for animals at pasture will vary with grazing conditions including the availability (tonnes DM/ha) and digestibility of the feed that will affect the energy used in ingesting herbage and in the distances walked, as will the distribution of watering points (Chapter 5), weather, topography and interactions between these factors. Farrell *et al.* (1972) found that the unit cost of walking (kJ/km per kg W) did not differ among sheep of similar skeletal size that were emaciated (27 kg) or in better condition (32 or 47 kg), and Mathers and Sneddon (1985) found with cattle that it did not vary with ambient temperature.

Information on the extent of the various activities of grazing animals has been reviewed by Arnold and Dudzinski (1978). The physical effort of selecting and detaching feed from the sward, compared with prehension from a trough, will have some effect on the energy cost of eating expressed as J/min, but the grazing animal will generally spend much more time in selecting and getting into its mouth the feed that it eats. For example, on a pasture providing abundant good quality herbage a sheep will often spend 6 h/d in grazing, or about 5 h more than a similar housed sheep would spend in eating the same amount of DM when feed of similar quality was presented. Expenditures of time and energy on rumination would probably be similar, but the grazing sheep could walk 3 km/d in feeding and for other reasons. The NE costs of these extra activities at pasture, using the values tabulated above and assuming level terrain, is 20.3 kJ/kg W or 50 kJ/kg $W^{0.75}$ for a 40 kg weaned sheep, which represents an increase of about 20% in NE_m (cf. Table 1.4).

There is experimental confirmation of this calculation (e.g. Langlands *et al.* 1963). Under extreme grazing conditions, the activities might exceed those in pens by 8 h for eating, and 5 km in walking plus a vertical component of 0.2 km. The NE cost of these activities is 38.6 kJ/kg W, which represents an increase of 35–40% in NE. This calculation has also been confirmed by experiment (Corbett 1981).

The increase in the ME_m for animals in any particular grazing conditions could be based on observation of the extent of their various activities and calculated as in the preceding paragraph. Generally the increase for animals not cold-stressed will be in the range of 10–20% in best grazing conditions, to about 50% for animals on extensive, hilly pastures where they walk considerable distances to preferred grazing areas or to water, or both. Conversely, strip-grazed animals presented with fresh pasture once or twice each day walk very short distances while grazing, depending on the stocking density on the strip.

The following approach to the prediction of ME_{graze} (MJ ME/d), to cover this range of grazing conditions has been devised:

$$ME_{graze} = [C.DMI(0.9 - D) + 0.0026\ H]\ W/k_m \qquad (1.22)$$

where:

H (horizontal equivalent of the distance walked) (km)
= T [(min(1, SR/SD)/(0.057GF +0.16) + M];

C = 0.02 (sheep, goats) or 0.0025 (cattle);

DMI = dry matter intake from pasture, kg/d, excluding supplementary DM;

D = digestibility of the dry matter (decimal);

GF = availability of green forage (t DM/ha when cut to ground level);
(If GF is <0.1 t/ha, total weight of forage is used in place of GF.)

M = total distance walked each day from pasture to milking shed (km);

SD = threshold for grazing density (animals/ha): 40 (sheep) or 5 (cattle);
SR = current grazing density (animals/ha.
T takes values that range from 1.0 to 2.0 as terrain varies from level to steep.

The first term in equation 1.22 defines the additional net energy expenditure in eating (MJ/kg W) incurred by grazing compared with housed animals. It is assumed that the energy expended in ruminating for a given quantity and quality of feed does not differ between grazing and housed animals, and no allowance is made for this activity. The values of the coefficient C imply that the relative rates of DMI (kg/h) from pasture by sheep and cattle are in the ratio 1:8.

The second term defines the net energy expenditure on walking (MJ/kg W), which decreases as green forage availability increases or as stocking density increases above the threshold and the animals walk correspondingly shorter distances to gain their feed. Conversely, as GF decreases the animals are likely to walk increasing distances to find this material. For example, in an extreme case, sheep searched cereal stubbles so that there was 80% of green in the forage they grazed although there was only 40 kg DM/ha as GF among the several tonnes of available DM/ha (Mulholland *et al.* 1976). However, at some very low value for GF, lower for sheep than for cattle, it can be expected that animals will abandon attempts at selection and simply eat what is immediately available. The maximum value for the horizontal equivalent of the distance walked (H) is 6.3 km/d. In arid or semi-arid areas with rather few watering points, animals may regularly walk considerable distances to drink (Chapter 5) in addition to those walked during grazing, and E_{graze} should then be increased by 0.0026 MJ/kg W for each extra km (horizontal) and 28 MJ/kg W per km (vertical component). To the extent that the stocking density of sheep or cattle on the current grazing area exceeds threshold values of 40 or 5 animals/ha, respectively, the distance walked is reduced.

The prediction of DMI is described in Chapter 6. If, for example, a 400 kg beast ate 7.2 kg DM/d with D = 0.7 from a flat pasture providing 2 t green forage DM/ha, E_{graze} is 3.6 MJ/d, which is an increment on minimum NE_m for an animal two years old (Table 1.5) of about 11%. For a 50 kg, two-year-old sheep on a similar pasture eating 1.1 kg DM/d, E_{graze} is 0.48 MJ/d which is an increment on minimum NE_m (Table 1.4) of about 10%. On steep country these calculated increments increase to 19 and 16% respectively.

Body condition

The maintenance requirements of animals are calculated as a function of their body weight with no adjustment for variation in their body condition (i.e. degree of fatness) as such. The implication that metabolism in adipose tissue and the work of carrying it contribute approximately pro rata with other tissues to the maintenance energy expenditure (kJ/kg $W^{0.75}$) is consistent with results from calorimetric studies on animals differing in body fatness. Graham (1967*a*, 1969*a*) measured the FHP of adult sheep of various breeds with fat contents in their fleece-free empty bodies varying from 7–33%. The FHP did not differ from the usual values (see p. 18) either within or between breeds at any degree of fatness except in one group that was very obese, and was abnormal owing to inappetance. In this instance FHP was elevated by 30–40%. Among other studies, McNiven (1984) also found that FHP kJ/$kg^{0.75}$ did not differ significantly between adult sheep after their initial mean live weight of about 60 kg had been changed by differential feeding to 90, 70 or 55 kg. However, Ball *et al.* (1998) found that differences in FM between and within breeds of sheep were reduced when expressed in relation to lean body mass rather than W.

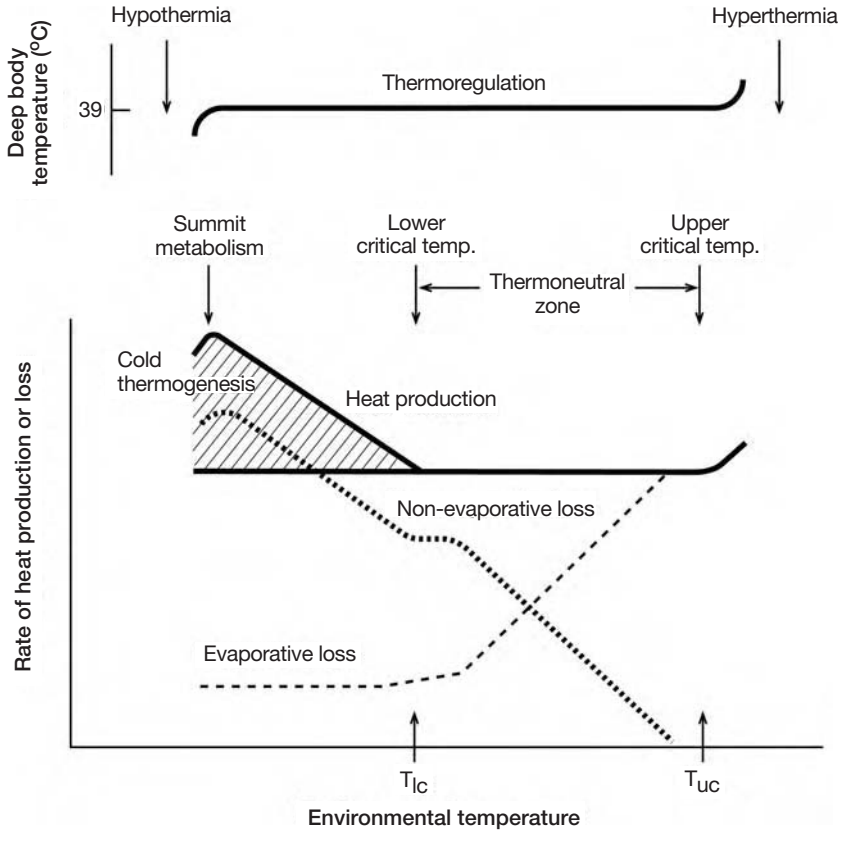

Fig. 1.3. Effect of environmental temperature on thermoregulation by the animal.

Energy expenditure in stressful climates

Mammals dissipate heat by evaporation, radiation, convection and conduction at a rate regulated to maintain a near-constant body temperature (T_b), which for ruminants is close to 39°C. This heat production arises from tissue metabolism and, in ruminants to a greater extent than in non-ruminants, from fermentation in the digestive tract. The animal's heat production (H) is largely independent of ambient (air) temperature (T_a) when this is within the zone of thermoneutrality (Fig. 1.3), and H is determined by the feed intake and the efficiency with which the energy of the feed is used. Thus for a growing animal:

$$H = ME_m + (ME1 - ME_m)(1 - k_g) \quad (1.23)$$

For a lactating animal with zero change in body energy, the term $(1 - k_l)$ replaces $(1 - k_g)$.

With T_a higher than the upper critical temperature the animal promotes heat loss by evaporation from the skin surface, by sweating, and via the lungs, by increasing respiration rate (panting). When the animal is heat stressed, productivity falls primarily because feed intake is reduced (see Chapter 6), but its elevated deep-body temperature increases metabolic rate and consequently its maintenance requirement. The lower limit of the zone of thermoneutrality is termed the lower critical temperature (T_{lc}). The T_{lc} for an animal varies with its thermal insulation or resistance to heat flow to the environment, and with its rate of heat production (H) in thermoneutral conditions (see Appendix IB). The resistance to heat loss is provided by: (*i*) the

tissue insulation (I_t); and (*ii*) the external insulation (I_e), which comprises the insulation provided by the hair coat or fleece (I_c), plus the insulation of the boundary layer of air surrounding the body (I_a) that varies with wind speed and the radiant environment. A sheep in full wool, for example, will be more resistant to cold (i.e. have a lower T_{lc},) than a shorn sheep. In both instances an increase in feed intake, and therefore in H (equation 1.23), will increase resistance to cold and reduce the T_{lc}.

When T_a falls below the T_{lc}, the animal must increase its metabolic heat production and augment H if it is to maintain T_b. The increase in the total heat production (MH) is lost by non-evaporative routes, and the rate of increase varies only with the animal's insulation ($I_t + I_e$). Again, compared with a sheep in full wool, one that is shorn will increase MH more rapidly as T_a falls; it will more rapidly approach maximum attainable heat production (summit metabolism) that will occur at a higher T_a. The summit metabolism of adult sheep (Bennett 1972) and lambs (Alexander 1962*a*) is of the order of 25 watts/kg $W^{0.75}$, or 2.16 MJ/kg $W^{0.75}$ per day, which is about eight times NE_m in thermoneutral conditions. This rate of heat production cannot be sustained for more than a few hours, but production at the rate of about half summit metabolism may be sustained for a number of days. Some T_{1c} values observed for sheep, cattle and goats in dry, still air, are given in Table 1.6.

Table 1.6. Some estimates of lower critical temperatures (T_{lc}) for sheep, cattle and goats in dry, still air

	Condition	Coat	T_{lc} (°C)
Sheep			
Lamb	Newborn		28
Lamb	1 month old		10
Adult	Maintenance	Shorn (5 mm)	25
Adult	Fasted	Shorn (5 mm)	31
Adult	Full fed	Shorn (5 mm)	18
Adult	Maintenance	50 mm	9
Adult	Maintenance	l00 mm	–3
Cattle			
Calf	Newborn	–	9
Calf	1 month old	–	0
Store	Maintenance	–	–16
Growing	0.4 kg LWG/d	–	–30
Growing	0.8 kg LWG/d	–	–32
Growing	1.5 kg LWG/d	–	–32
Beef cow	Maintenance	–	–21
Dairy cow	9 litres milk/d	–	–17
Dairy cow	23 litres milk/d	–	–26
Dairy cow	36 litres milk/d	–	–33
Goats			
Adult[A]	Maintenance	57 mm	9
Adult[B]	Maintenance		13

Sources: Sheep and cattle, NRC (1981b) and Webster (1983). Goats [A] Holmes and Moore (1981), [B] Magee (1924).

Evaluation of E_{cold}

There is some evidence (Nicol and Young 1981) that ME may be used to maintain body temperature with an efficiency of only 0.5–0.6 when a large amount of cold water is drunk rapidly. However, this is likely to occur only if $T_a < T_{1c}$ (White 1979) and it is usually assumed (e.g. ARC 1980) that the efficiency is 1.0. Consequently, the value of E_{cold}, if any, is the same as the additional ME required to alleviate cold stress.

Table 1.7. Values for total thermal insulation ($I_t + I_e$, °C m^2 d/MJ) showing effects of rainfalls[A] at several wind velocities[B]

Coat depth (mm)	Wind (km/h)											
	Calm			5			10			20		
	Rainfall (mm/d):			Rainfall (mm/d):			Rainfall (mm/d):			Rainfall (mm/d):		
	0	10	30	0	10	30	0	10	30	0	10	30
Lamb[C]												
6	3.36	2.79	2.74	2.62	2.26	2.23	2.38	2.09	2.06	2.13	1.90	1.88
8	3.54	2.97	2.87	2.78	2.40	2.34	2.52	2.21	2.15	2.23	1.99	1.95
10	3.72	3.16	3.00	2.93	2.55	2.44	2.65	2.33	2.25	2.32	2.08	2.02
12	3.90	3.34	3.14	3.07	2.69	2.55	2.77	2.46	2.34	2.41	2.18	2.09
14	4.07	3.52	3.27	3.22	2.84	2.66	2.89	2.58	2.43	2.50	2.27	2.16
Adult sheep												
5	3.36	2.77	2.74	2.60	2.23	2.21	2.36	2.06	2.04	2.11	1.88	1.87
10	3.92	3.31	3.14	3.05	2.64	2.53	2.75	2.41	2.32	2.40	2.14	2.07
20	4.99	4.40	4.00	3.91	3.50	3.21	3.48	3.14	2.90	2.94	2.68	2.50
30	5.98	5.43	4.89	4.72	4.32	3.92	4.17	3.83	3.50	3.45	3.20	2.95
40	6.92	6.40	5.78	5.48	5.08	4.63	4.81	4.48	4.10	3.93	3.68	3.40
50	7.81	7.30	6.65	6.19	5.81	5.32	5.41	5.09	4.68	4.38	4.14	3.83
Calf[D]												
10	3.03	2.49	2.34	2.16	1.82	1.73	1.86	1.59	1.51	1.51	1.32	1.27
15	3.44	2.92	2.66	2.46	2.13	1.96	2.09	1.83	1.69	1.64	1.47	1.38
20	3.84	3.34	3.00	2.76	2.43	2.20	2.32	2.06	1.88	1.78	1.61	1.49
25	4.22	3.74	3.34	3.04	2.72	2.45	2.54	2.29	2.08	1.91	1.75	1.61
30	4.59	4.14	3.69	3.31	3.01	2.71	2.76	2.51	2.28	2.04	1.88	1.72
35	4.96	4.51	4.03	3.58	3.28	2.96	2.96	2.73	2.47	2.16	2.01	1.84
Adult cattle												
15	4.47	3.92	3.65	3.44	3.09	2.92	3.05	2.78	2.64	2.59	2.40	2.31
20	4.92	4.39	4.03	3.77	3.43	3.19	3.31	3.04	2.85	2.74	2.56	2.43
25	5.36	4.85	4.42	4.09	3.75	3.47	3.56	3.30	3.07	2.89	2.72	2.57
30	5.80	5.30	4.82	4.41	4.08	3.75	3.81	3.55	3.29	3.04	2.87	2.70
35	6.23	5.74	5.22	4.72	4.40	4.05	4.05	3.80	3.52	3.19	3.02	2.84
40	6.65	6.18	5.63	5.03	4.71	4.34	4.30	4.04	3.75	3.33	3.17	2.98

[A] Calculated with equation (1 B.6).

[B] Wind velocities at animal height: assumed to be 0.4 of velocity measured at 10 m above ground by meteorological stations.

[C] At birth, and approximately correct to about 15 kg W. For lambs newborn, and therefore wet, use 10 mm rainfall values.

[D] Insulations for a calf two days old. Approximately correct up to 100 kg W provided all values are increased by 0.036 per day of age to a maximum of +0.96 at age 28 days or more.

Table 1.8. Lower critical temperatures (T_{lc}, °C; rounded to whole numbers) of animals with a metabolisable energy intake sufficient for maintenance (ME_m) in thermoneutral conditions

Coat depth (mm)	Wind (km/h)											
	Calm			5			10			20		
	Rainfall (mm/d):			Rainfall (mm/d):			Rainfall (mm/d):			Rainfall (mm/d):		
	0	10	30	0	10	30	0	10	30	0	10	30
Lamb (5 kg W)												
6	21	24	24	25	26	27	26	27	27	27	28	28
8	20	23	23	24	26	26	25	27	27	26	28	28
10	19	22	23	23	25	26	24	26	26	26	27	28
12	18	21	22	22	24	25	24	25	26	26	27	27
14	18	20	22	22	24	24	23	25	26	25	26	27
Adult sheep (50 kg W)												
5	19	22	22	23	25	25	25	26	26	26	27	27
10	16	16	20	21	23	24	22	24	25	24	26	26
20	10	13	16	16	18	20	18	20	22	21	23	24
30	5	8	11	12	14	16	15	17	18	19	20	21
40	0	3	6	8	10	12	11	13	15	16	17	19
50	– 5	–2	1	4	6	8	8	10	12	14	15	16
Calf (2 days old, 40 kg W)												
10	22	25	26	26	28	29	28	29	30	30	31	31
15	20	22	24	25	27	28	27	28	29	29	30	31
20	18	20	22	23	25	26	26	27	28	28	29	30
25	16	18	20	22	24	25	24	26	27	28	29	29
30	14	16	18	20	22	24	23	25	26	27	28	29
35	12	14	16	19	20	22	23	24	25	26	27	28
Calf (28 days or older, 70 kg W)												
10	10	14	15	16	18	19	18	20	20	20	22	22
15	8	11	13	14	16	18	17	18	19	20	21	21
20	5	8	11	12	14	16	15	17	18	19	20	21
25	3	6	8	10	12	14	14	15	17	18	19	20
30	0	3	6	9	11	13	12	14	15	17	18	19
35	–2	1	4	7	9	11	11	13	14	16	17	18
Adult cattle (500 kg W)												
15	2	6	8	10	13	14	13	15	16	17	18	19
20	–1	3	6	8	10	12	11	13	15	16	17	18
25	–5	–1	3	5	8	10	9	11	13	16	16	17
30	–8	–4	0	3	5	8	7	9	11	13	14	16
35	–11	–8	–4	0	3	6	5	7	10	12	13	15
40	–15	–11	–7	–2	0	3	3	6	8	11	12	14

See footnotes to Table 1.7.

Effect of rain. Heat loss by the animal is increased during and for some time after rainfall because replacement of air in the pelage by water increases thermal conductivity and reduces I_e; because heat energy is used to evaporate the water; and because of induced physical activities by the animal (e.g. shaking). Quantitative definition of the effects on heat loss is difficult because

there is little information on the relationship between rainfall and the extent to which the fleece, or hair coat, becomes wet. Mount and Brown (1982) suggested that when a sheep has a wet fleece there is a reduction in I_e by about 30%, and that total insulation values should be adjusted on this basis for (time wet h/24) = t_w.

Total insulation value in rain = $I_t + (1 - 0.3t_w)I_e$ where I_e is $(I_{total} - I_t)$

An alternative approach was used by Freer *et al.* (1997) in which, in place of t_w the extent of wetting is predicted from rainfall (R, mm/d) and coat depth (F mm, sheep and cattle): total insulation in rain = $I_t + [1–0.3(1–\exp(–1.5R/F))]I_e$ (see Appendix 1B). This implies that for a 5 mm coat, there will be a full wetting effect when there is about 15 mm rain/d, but with this rainfall a 50 mm coat will be only 35% wet. Thus the problem of partial wetting is accommodated, though there remains some difficulty in identifying from daily precipitation the diurnal pattern of wetting and the effects on energy expenditure over 24 h periods. Some predictions of the effects of rainfall on total insulation and T_{lc}, are given in Tables 1.7 and 1.8; in general, these are approximately the same as those predicted for similar conditions by the equation of Mount and Brown (1982). Newborn animals will be wet, and appropriate insulation values and T_{lc} should be read from the 10 mm rainfall columns in Table 1.8.

Effect of wind. At a given T_a, the effective temperature is lower in windy conditions than in still air. Note that wind velocity at the height of the animal may be taken to be 0.4 × the velocity measured by meteorological stations at the standard height of 10 m above the ground (Mount and Brown 1982).

Cold nights with clear sky. The rate of heat loss by long-wave radiation from the animal increases with the extent to which the temperature of its coat surface exceeds the mean radiant temperature (T_r) of its surrounds. At pasture, the ground and the sky each subtend half the total solid angle at the animal, and so $T_r = 0.5(T_{gound} + T_{sky})$. T_{ground} approximates T_a and when the sky is totally covered by cloud T_{sky} also approximates T_a. In the total absence of cloud, $T_{sky} = T_a - 20$ (Monteith 1973). For air temperatures between 10°C and –10°C it can be shown (Mount and Brown 1982) that the operative temperature (T_o, Winslow *et al.* 1937), which takes account of the consequences for the animal of radiative heat loss in these conditions, is $(T_a - 5)$. In the Australian climate it is sufficient to make this adjustment to all night-time T_a of 10°C or less.

To determine E_{cold}:

$$E_{cold}\ (ME, MJ/d) = A(T_{lc} - T_a) / (I_t + I_e) \qquad (1.24)$$

where:

A (the surface area of the animal, m^2) = 0.09 kg $W^{0.66}$

(The derivation of this equation is given in Appendix 1B.)

Appropriate values of total insulation ($I_t + I_e$, °C m^2 d/MJ) for different animals, at different wind speeds and rainfall levels are shown in Table 1.7. Corresponding values for the lower critical temperature are listed in Table 1.8. These tables were prepared from the equations presented in Appendix 1B. Negative or zero values of E_{cold} are ignored.

Effect of heat

If T_a and T_r exceed the temperature of the skin surface of the animal it cannot lose heat by conduction, convection, or radiation, and will gain heat by these routes. It must increase insensible (evaporative) heat loss, which, as noted earlier, is its response to thermal environments above the upper critical temperature. The effectiveness of this response in holding T_b down towards 39°C diminishes as the relative humidity (RH) of the air increases, and it will be wholly ineffective at

RH = 100. Fortunately such extreme climatic conditions, if they occurred at all, would persist for only a short time for otherwise the animal would soon die from hyperthermia. It can store some heat in its body, manifest as a rise in T_b that does occur during the daytime in hot climates, and then dissipate this heat during cooler daytime periods and at night. The energy costs of sweating and panting to increase evaporative heat loss, as such, will have negligible effect on the total heat load of the animal, and when the contribution of the climatic environment to the load is high the contribution of H (equation 1.23) is reduced because of a decrease in feed intake.

There has been much study of various aspects of heat stress and animal performance but, unlike cold stress, there are no well-established bases for quantitative definitions of effects. One problem is that when studies are made in a 'climate laboratory' the imposed heat load is often set and not varied with time. As shown by Murray (1982), the observed physiological responses may not be applicable to animals in their natural field environment where there will be circadian variation in the heat load. Studies by Hales and Findlay (1968) and Hales (1973) led the NRC (1981*a*) to propose that the type and intensity of panting by an animal can provide an index for an appropriate adjustment in maintenance requirement. It suggests an increase of up to 7% when there is rapid shallow breathing, and of 11–25% for deep open-mouth panting.

Acclimatisation

The term acclimatisation is used to describe adaptive changes in response to changes in the natural weather (Bligh and Johnson 1973). Although not recognised in the strict usage by physiologists, adaptations include modifications in behaviour such as the use of minor variations in topography, huddling in groups and changes in posture to minimise exposure and heat loss in cold, and seeking shade or wading into water in heat. Such effects cannot be allowed for in the calculation of E_{cold} except so far as tree windbreaks, for example, affect observed wind speed and T_a. The physiological adaptations to cold result in a persistent change in basal metabolic rate.

Sheep experience a sudden major change in their thermal environment when they are shorn. There is a great reduction in I_e and there may be high mortality during the following one to two weeks (Hutchinson 1968), especially if there is cold wind and rain; hyperactivity and degeneration of the adrenal cortex is often observed post-mortem (Panaretto and Ferguson 1969). Problems of thermoregulation immediately after shearing ('off-shears') can be compounded by a reduction in the time spent grazing (Hutchinson and McRae 1969) that probably signifies a lowered feed intake as has been observed in penned sheep immediately after shearing, though after a few days the intake generally increases and becomes higher than it was before shearing (e.g. Donnelly *et al.* 1974). Calculation of T_{1c} and E_{cold} to assess additional ME required may be of little practical use if the sheep will not eat extra feed, but will show why there can be catastrophic mortality in sheep off-shears and will highlight the desirability of providing shelter. Subsequent acclimatisation was studied by Farrell and Corbett (1970) who intermittently brought sheep from pasture into respiration chambers for short periods to measure FHP in temperatures of 21–26°C; mean daily minimum and maximum outdoor temperatures over several months were 1.5 and 11.6°C. FHP increased after shearing (day 0) by an observed maximum of 44% at day 13, and did not decrease to pre-shearing values until day 135.

Calculation of E_{cold} does not allow for the long-term effects of acclimatisation by sheep. No studies have been made on cold acclimatisation by cattle in Australia where, probably, it will generally be of minor significance. From consideration of measurements by Young (1975) of the

resting metabolic rate of beef cows after exposure for several weeks to various ambient temperatures, the NRC (1981*a*) proposed that for each 10°C these temperatures were above or below 20°C the NE_m of cattle determined at 20°C should be respectively decreased or increased by 9.1%. The value given for NE_m at 20°C, taken to represent thermoneutrality, was 0.32 MJ/kg $W^{0.75}$; this is similar to the 0.33 MJ/kg $W^{0.75}$ for adult cows predicted with equation 1.19. The NRC (1981*a*) proposition might be used to assess approximately how cattle NE_m was altered by acclimatisation to long periods of cold weather, and an increased ME_m persisted even when T_a was higher than T_{lc}. The effect on ME_m for *B. taurus* (equation 1.19) would then be assessed as:

$[(1 + 0.0091\ C)(0.39\ W^{0.75} \exp(-0.03A))]/k_m$

where C is $(20 - T_a)$ °C. A similar adjustment might be made for sheep (with the coefficient 0.28 in place of 0.39).

Requirements for survival (drought feeding)

Animals fed for survival will generally be given minimal amounts of feed, and so will have a reduced ME_m. In the original equation of Graham *et al.* (1974) to predict BMR, the term 2.8G could have a negative value so that predicted maintenance requirements would decrease with loss in live weight, and with a reduction in the value of the 0.046 D term as feed intake decreased. The rate of decrease in BMR towards a lower value would diminish over a period that varied in duration with degree of undernutrition. This change is not easily defined, and so the decrease in the maintenance metabolism that undoubtedly occurs when animals are fed for survival has not been formally systematised in the generalised equations 1.19 and 1.20. It can be of major economic importance in practice; Table 1.3 shows that the amount, and therefore cost, of feed given to animals in drought may be at least 10% less than would be given when the amount is calculated with the first term of equation 1.19.

The policy adopted in long-term drought feeding must take account of several important considerations. In most of the trials summarised by CSIRO (1958) and Morris (1968), and shown in Table 1.3, the animals were tied in stalls or kept in pens or small yards, they were not cold stressed, and sometimes they were individually fed. If, in practice, animals are drought-fed on bare pastures they can expend considerable energy on physical activities. For example 300 kg cattle would expend about 2.4 MJ of NE in walking 3 km on level ground and, without making any allowance for energy costs they could incur in attempts to gain residual herbage, the 2.4 MJ is nearly 10% of 'ordinary' NE. If their feed allowance had been reduced by 10%, the effective deficit in NE provided would thus be about 20%. The same consideration applies to cattle at other W and to sheep.

If feed allowances were reduced, the animals would have to be given extra amounts in advance of the onset of weather expected to cause cold stress, supposing this could be forecast, so that they would be better able to withstand such conditions with increased heats of fermentation and tissue metabolism. Moreover, if the animals had been kept on a reduced allowance for some time, it is possible that skin thickness and subcutaneous fat would be decreased, and they would have a short fleece or hair coat so that their insulation and ability to withstand cold stress would be diminished in comparison with animals given an unreduced allowance.

A further problem could arise with animals group fed, which is the usual practice. In these conditions the proportion of animals that failed to gain an adequate share of the feed provided would probably increase as the allowance was reduced, though this effect might be minimised by feeding once or twice weekly rather than daily.

From these considerations it is recommended that equation 1.19 should be used as a guide to the amounts of feed that should initially be given to drought-fed animals. Their performances should be monitored to determine whether, and to what extent, allowances could be reduced. Calculation of the additional ME required by animals that are pregnant or lactating is described in following sections.

Application of the generalised equations

In equation 1.19, the variation in energy expenditure associated with the quantity of ME used directly for production (0.1 ME_p) can be regarded as one of the four terms that together define the total 'maintenance' energy expenditure. Alternatively it may be regarded as a metabolic cost associated with synthetic processes for production. From this standpoint, the ME required to achieve the production of any given liveweight gain or quantity of milk will be the energy gain in the production divided by k_g or k_l and then incremented by 10%. Thus for 1 kg liveweight gain (say 20 MJ) with $k_g = 0.51$ the ME required in addition to ME_m (including ME_{graze} and E_{cold}) will be $1.1(20/0.5) = 44$ MJ.

To simplify use of equation 1.19 for ration formulation, this alternative approach of regarding 0.1 ME_p as a charge on the energy cost of production is adopted. It implies that if cattle of, say, 150 and 300 kg W are both gaining 1 kg/d then, as could be expected, the maintenance metabolism of the smaller animal is increased to a relatively greater extent than that of the larger.

With equation 1.20, ME_m is calculated with all four terms, including 0.09 MEI, and, the energy gain by the animal is (MEI – ME_m) multiplied by k_g or k_l. The equivalent liveweight gain or milk production is then estimated (see pp. 34 and 46).

It should be noted that with the use of equations 1.19 and 1.20:

(*i*) M/D is not to be adjusted for level of feeding (see p. 12),

(*ii*) the value of k_g for any particular diet is not varied for level of feeding,

(*iii*) the term 0.1 ME_p is not to be used in assessing ME requirements for pregnancy because k_c already allows for augmentation of maternal metabolism (see *Net energy requirements for gestation*).

Net energy requirements for gestation

ARC (1980) describes the rates of accretion of energy and nutrients during foetal and conceptus growth with Gompertz equations. While any particular set of data on the growth of the foetus and associated tissues and organs might be described a little more precisely with other forms of equation, the Gompertz model, overall, is generally the most robust and introduces least errors in predictions when these are made for early or late stages of pregnancy (Robinson and McDonald 1979). The Gompertz equation that describes the weight or energy content of the foetus or gravid uterus (Y) at time t (days) after conception is of the general form of equation 1.25.

$$Y = SBW \exp(A - B (\exp(-Ct)) \quad (1.25)$$

where SBW is the scaled birth weight (see below)

The daily gain in weight or in energy content is calculated as the differential:

$$dY/dt = B C \exp(-Ct) Y \quad (1.26)$$

These equations and the parameters in Table 1.9 are **adopted** in this Report.

Table 1.9. Parameters for the prediction of ME requirements for gestation

	Foetus			Gravid uterus		
	A	B	C	A	B	C
Sheep						
Weight (kg)	2.75	17.99	$1.75*10^{-2}$	5.17	8.38	$6.08*10^{-3}$
Energy (MJ)	4.70	21.44	$1.73*10^{-2}$	7.64	11.46	$6.43*10^{-3}$
Cattle						
Weight (kg)	5.94	12.91	$6.21*10^{-3}$	6.75	7.71	$4.06*10^{-3}$
Energy (MJ)	11.95	16.59	$3.34*10^{-3}$	349.22	349.16	$5.76*10^{-5}$

The values of the parameters in Table 1.9 are derived from those of the ARC (1980), which predicted $\log_{10}Y$ and were appropriate for specific birth weights: a 4 kg lamb at 147 days and a 40 kg calf at 281 days. The inclusion of SBW, the ratio of the expected birth weight of the foetus to either of these specific weights, allows the original equations to be applied more generally. The functions for predicting the weight of the gravid uterus are used to establish the maternal weight of the cow or ewe during gestation, before calculating her maintenance requirements for energy.

To predict the mother's net energy requirements for pregnancy, the 'gravid uterus' parameters are to be used. These will allow for growth of the uterus, as well as the foetus; they might not, however, properly allow for concurrent udder growth, especially towards term when colostrum is secreted (Mellor and Murray 1985). For ewes, the value of Y can be increased, with little error, in direct proportionality to the number of young when such are anticipated from the particular type of ewe, or because pasture conditions will promote multiple births.

In the absence of corresponding information for goats, the sheep coefficients may be used for this species also (AFRC 1998).

ME requirements for gestation

The ARC (1980) found that estimates, for both sheep and cattle, of the efficiency of use of ME for conceptus energy gain (k_c) did not differ greatly from a mean of 0.133. This may appear to be a surprisingly low efficiency for so important a function, but arises from the method of calculation, which yields a gross, and not a net, efficiency value. All energy costs of gestation, including growth and maintenance of uterine and other tissues, the maintenance of the foetus and any augmentation of maternal metabolism, are expressed as a function of gain in the conceptus only. Consequently, the calculation of the ME requirements for the mother's maintenance during gestation uses her maternal weight and excludes the term 0.1 ME_p from equation 1.19. There is evidence from sheep (Robinson *et al.* 1980) that k_c, like k_m etc., varies with M/D. With M/D = 10.5, k_c was 0.145 and its value decreased by 0.029 per unit decrease in M/D, unless maternal energy loss contributed to foetal energy gain. It appears that maternal energy contributions are used with greater efficiency than dietary ME, and these contributions are likely to be greatest when diet quality is low. Consequently, although k_c for dietary ME alone may be less than 0.10 when M/D is nine or less, the overall gross efficiency of use of maternal plus dietary energy may remain around 0.13–0.15. It is uncertain whether k_c would increase with M/D greater than 10.5.

The estimates in Table 1.10 of the ME required in pregnancy by ewes (and goats) and cows in addition to ME requirements for their own maintenance have been calculated from equation 1.26 and the energy parameters for the gravid uterus in Table 1.9.

Table 1.10. ME required (MJ/d) for pregnancy by ewes (and goats) and cows, in addition to maternal ME_m, for a lamb (and kid) birth weight of 4 kg and a calf birth weight of 40 kg (requirements for other birth weights to be calculated pro rata)

Weeks before term:	12	8	6	4	2	Term
Ewes (goats)	0.4	1.1	1.7	2.6	3.8	5.3
Cows	8.2	14.2	–	24.7	–	42.9

Net energy requirements for liveweight gain

The NE requirements equal the heats of combustion of the fat and protein gains in the body, which are (ARC 1980) 39.3 kJ/g fat and 23.6 kJ/g crude protein (i.e. ether-extracted organic matter), but substantial problems arise in the application of this information:

(*i*) The relative proportions of fat and protein in unit gain or loss in tissue mass from the body vary with the breed, sex and age (live weight) of the animal, and with the rate of gain or loss.

(*ii*) There is variation in the water content of tissue gain, reflecting gain or loss of water associated with protein deposition or catabolism.

(*iii*) Expression of unit gain or loss of tissue mass, i.e. empty body change, in terms of change in live weight is uncertain because of concurrent changes in the mass of gut contents.

The ARC (1980) examined data from many sources on the protein and fat contents of animals of various ages slaughtered at various empty body weights (EBW), and derived equations relating the energy content (heat of combustion) of empty body gain to EBW. Their derivation inevitably involved a good deal of compromise owing to the heterogeneity in the data. In addition, the equations had to be expressed in terms of live weight (W) and liveweight gain (LWG) for practical application. The conversions used for weaned animals were: W (sheep) = 1.09 (EBW + 2.9); W (cattle) = 1.09 (EBW + 14); and LWC (sheep and cattle) = 1.09 EBG, where EBG is empty body gain.

The data used by the ARC (1980) to derive equations to predict the energy content of liveweight gain by Merino sheep were almost wholly Australian, and included several sets from Australia for other breeds, but the equations appear to yield some anomalous results and present some difficulties.

For example, the MJ/kg gain values for milk-fed lambs appear to be low, especially at low rates of gain (e.g. 7.2 MJ/kg wool-free empty body gain at 100 g LWG/d). They also appear to be low for young growing sheep; at 15 kg live weight the values vary with sex in the range of 7.8–9.2 MJ/kg. Equations presented for males, castrates and females of non-Merino breeds are of the form (MJ/kg gain = a + b W) and so make no allowance for variation in rate of gain. They were derived from, and are applicable to, sheep with maximum 50 kg empty body weight, which is about 57 kg live weight.

For greater W, predicted values tend to become improbable; at 70 kg, for example, they are about 27 MJ/kg gain for males and castrates, but 33.6 MJ/kg for females. An equation of the same form for Merino castrates has been calculated from the data on empty body composition that were presented and, using the ARC (1980) method to convert these to a live weight basis, is (MJ/kg LWG = 1.53 + 0.51 W). It will be seen that improbable values are predicted for live weights greater than about 50 kg.

The prediction equation of MAFF (1984*a*) for sheep allows for variation with rate of gain, but not with breed or sex, and it is not applicable to unweaned lambs. It predicts values that at

15 kg W are around 15 MJ/kg LWG, increasing to about 25 MJ/kg LWG at 70 kg W.

The ARC (1980) quadratic equation for the energy value of LWG in cattle allows for variation with rate of gain, sex and maturity type, with breeds grouped as small, medium or large; a classification later revised (AFRC 1990) as 'early', 'medium' or 'late' maturing. Data of Garrett (1980) and Robelin and Daenicke (1980) are in agreement with the ARC (1980) that, within a breed, heifers have a greater proportion of fat in LWG than steers, and bulls have a lesser proportion, in both instances to an extent approximating to the adjustments of ± 15% to predicted energy values.

Those data, and the equation of Van Es (1978) to predict energy gains by Friesian bulls, also confirm the wide variation between breeds. Their 'mean values' relate to protein concentrations in EBW gain that decline from 181 g/kg at 50 kg EBW, to 140 g/kg at 500 kg but information reviewed by INRA (1978) shows that values of around 200 g/kg, and correspondingly lower energy contents of gain, occur in some European breeds such as Charolais even at live weights approaching 500 kg. Robelin and Daenicke (1980) classify a number of breeds as 'very early', 'early', or 'late' maturing, and the associated variation in the composition of gain is approximately encompassed by the ARC (1980) adjustments of ± 15% for breed size.

Prediction of the composition of gain in growing animals

In view of the uncertainties associated with the use of the several methods for predicting the composition of gain, discussed above, another approach has been developed. It takes account of the information on mainly 'British' breeds of cattle and sheep, and Merino sheep, reviewed by ARC (1980); on 'European' breeds of cattle, and on sheep, reviewed by INRA (1978); and of reports made after the publication of those two monographs, which have been reviewed by Greenhalgh (1986). In addition, Garrett (1987) discussed the relationship between energy metabolism and the amounts of protein and fat deposited in growing cattle. He showed that when the energy content of empty body gain is known (MJ/kg EBG = X), the proportions of fat and protein in the gain (F_p and P_p, kg per kg EBG) can be predicted as:

$$F_p = 0.0287X - 0.142 \quad (1.27)$$

$$P_p = 0.256 - 0.0067X \quad (1.28)$$

He also concluded (W. N. Garrett pers. comm.) that extreme values for the composition of gain in growing cattle were likely to be about:

	Energy MJ/kg EBG	Fat g/kg EBG	Protein g/kg EBG
Lower limit:	8.4	100	60–80
Upper limit:	29.3	700	200

Thus a gain of 1 kg in a very young animal could contain 200 g protein, 100 g fat, and 700 g water plus ash, representing a ratio of protein to water plus ash of 0.29, which is within the normal range (Garrett 1987) of 0.25–0.33.

The basic assumption made by Garrett (1987), viz. 730 g water, 216 g protein and 54 g ash per kg fat-free empty body in bovines, is also valid for sheep (e.g. Searle and Griffiths 1983). The equations given below to predict the composition of gain yield values that are consistent with these relationships among energy, fat and protein. The prediction equations are applicable to sheep as well as to cattle, and allow for variation with their breed, sex and rate of gain.

This versatility is achieved by identifying a **Standard Reference Weight** (SRW) appropriate for each type of animal. In concept, the SRW for any particular breed and sex of cattle or sheep is approximately the live weight that would be achieved by that animal when skeletal development

is complete and the condition score is in the middle of the range, i.e. condition score 3 for beef cattle and sheep and condition score 5 for dairy cattle (see p. 52). Thus the SRW for breeds sometimes described as 'small' (ARC 1980), 'small-frame' (NRC 1984), or 'early-maturing' (Robelin and Daenicke 1980) are lower than those for 'medium', 'large', or 'late-maturing' breeds. Within a breed the SRW increase in the order: females, castrates, males.

The live weight of the animal expressed as a proportion of its SRW (i.e. its degree of development) and referred to as its relative size, Z (see also Chapter 6) can be used in a single set of equations (Corbett *et al.* 1987*b*) to predict the fat and protein, and hence the energy, in gain for growing animals in all breeds of sheep and cattle that are currently of commercial importance in Australia. However, to accommodate the 'large' European breeds (Charolais, Simmental, Chianina, Maine Anjou, Limousin, Blonde d'Aquitaine) that deposit relatively more protein than other cattle breeds, one coefficient in these equations is modified. In the mature animal, where Z approaches 1.0, the composition of gain or loss is predicted from its body condition, as discussed later.

Prediction equations for growing animals

The equations **adopted** in this Report predict the composition of empty body gain (EBG).

Given that:

(*i*) energy retained (ER, MJ) by the animal as body tissue = $k_g \times$ (ME intake surplus to other needs); and

(*ii*) EVG is the energy content of empty weight gain (MJ/kg EBG) predicted with equation 1.30 and EBG = 0.92 LWG, then

$$LWG = ER / (0.92 EVG) \tag{1.29}$$

The equations below are applicable to all breeds of sheep, and to all breeds of cattle including *Bos indicus*, with the exception that the coefficient b differs for some large lean breeds of cattle, e.g. Charolais, Chianina, Blonde d'Aquitane, Limousin, Maine Anjou, and Simmental.

$$\text{Energy or fat/kg EBG} = (a + cR) + (b - cR) / [1 + \exp(-6(Z - 0.4))] \tag{1.30}$$

$$\text{Protein/kg EBG} = (a - cR) - (b - cR) / [1 + \exp(-6(Z - 0.4))] \tag{1.31}$$

where:

Z = current W /SRW, with a maximum value of 1.0;

R = adjustment for rate of gain or loss = (L – 2) where L (see Glossary) is level of feeding: MEI/ME_m.

The values of the coefficients a, b and c are set out in Table 1.11. The **A** values for coefficient b apply to all sheep and to all cattle except the large lean breeds specified above (**B** values). Intermediate values are used for crosses (e.g. **A**x**B**) between the two types of cattle

The predicted energy content of EBG ranges from about 9 MJ/kg at birth to about 27 MJ/kg at maturity in **A** type animals or to about 23 MJ/kg in **B** type cattle. The respective values for fat content of EBG are about 120 g/kg, 630 g/kg and 520 g/kg. For protein content of EBG, they are, respectively, about 195 g/kg, 75 g/kg and 95 g/kg.

The adjustment for rate of gain (R) has decreasing effect as Z increases. This is consistent with expectation in that gain in animals approaching maturity will contain a larger proportion

of fat than in younger animals, so that an increase in gain by the former will have proportionately less effect on fat and energy contents.

Table 1.11. Parameters for predicting the energy, fat and protein content of empty body gain in immature animals

	All animals		Animals of type		
			A	B	AxB
	a	c	b	b	b
Total energy MJ/kg	6.7	1.0	20.3	16.5	18.4
Fat energy MJ/kg	1.7	1.1	23.6	19.3	21.5
Protein energy MJ/kg	5.0	0.1	3.3	2.8	3.0
Fat g/kg	43	28	601	490	545
Protein g/kg	212	4	140	120	130

Possible values for the SRW to be assigned to various breeds of cattle and sheep are shown in Table 1.12, but genotypic variation within a breed will not be encompassed by a single generalised set of values. In each particular application, the SRW should be based on local information about the type of animals under consideration. The SRW are also employed in the prediction of feed intake (Chapter 6), the net protein requirements for wool growth (see p. 93) and the change in W per unit change in condition score (see p. 58).

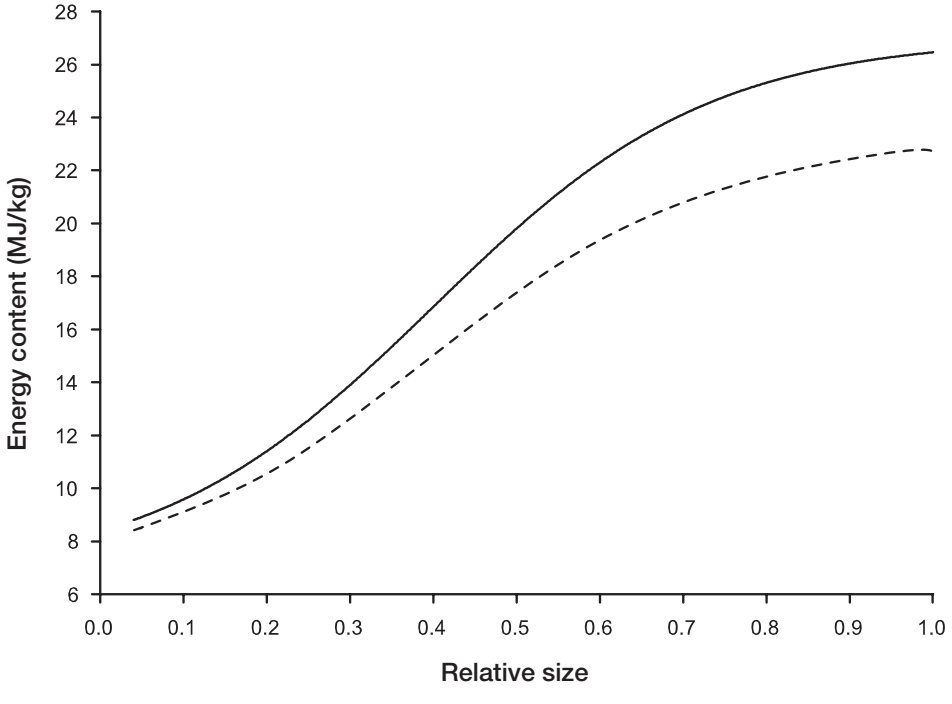

Fig. 1.4. The energy content of empty body gains (MJ/kg) with increasing relative size (Z) of the growing animal (see equation 1.30). Equation 1.30 is used with B coefficients for the large lean cattle breeds (dashed line) or with the A coefficients for sheep and other breeds of cattle (solid line).

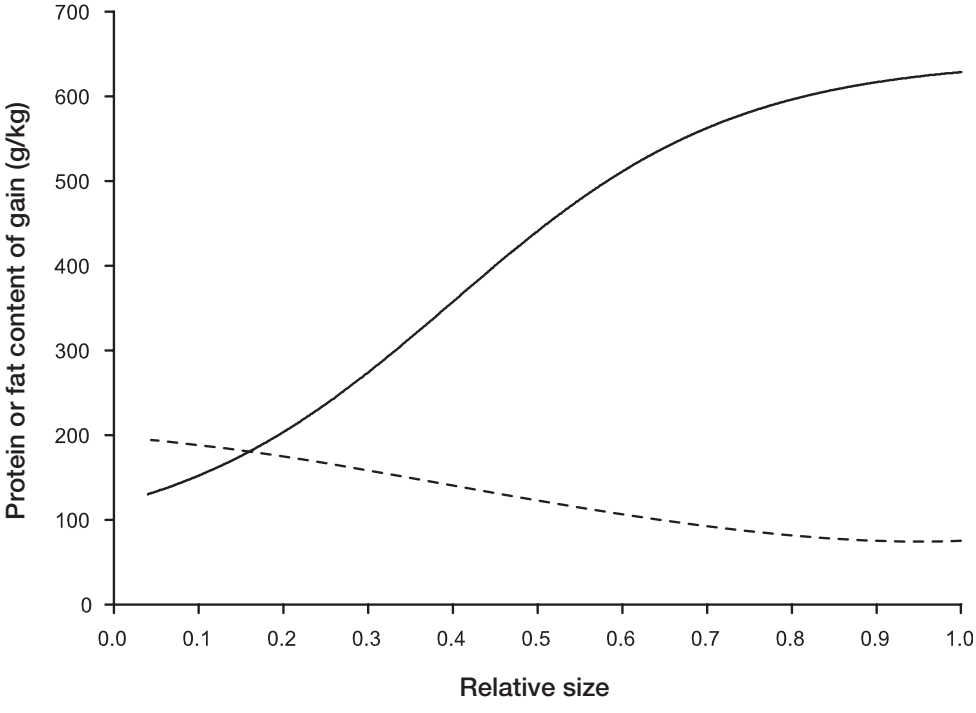

Fig. 1.5. Fat (solid line) and protein (dashed line) contents of empty body gain (g/kg) with increasing relative size of the growing animal, using the A coefficients in equations 1.30 and 1.31.

Values for the composition of gain predicted with the above equations for various SRW and a range in Z up to 1.0 are shown in Table 1.13. They are illustrated in the corresponding Figs 1.4 and 1.5.

The database for goats, reviewed by Sahlu *et al.* (2004), indicates that the composition of gain in immature goats is very similar to that in sheep.

Compensatory gain

The first cause of compensatory or 'catch-up' growth by immature animals given abundant feed after a period of undernutrition is probably an above-average feed intake (Thornton *et al.* 1979; Graham and Searle 1979) though this may not occur immediately with re-alimentation (Butler-Hogg and Tulloh 1982). Increased feed intake will cause substantial increases in gut-fill and live weight, but there is also evidence of an increase in the gross efficiency of conversion of feed to body gain. This may be due in part to a greater net efficiency (k_g) of ME use (Graham and Searle 1979; Thomsen *et al.* 1980; Thomsen *et al.* 1982) because a higher proportion of the live-weight gain is stored as protein and water (Oddy and Sainz 2002). There is also a reduced maintenance requirement carried over for some time from the period of undernutrition (see p. 19) with the result that the proportion of total feed intake available for production will be greater than with animals continuously well fed. Such increases in efficiency are likely to be transitory (Butler-Hogg and Tulloh 1982), and it is concluded that the energy content of compensatory gains should be calculated in the same manner as for gains during uninterrupted growth (equation 1.30).

Table 1.12. Possible Standard Reference Weights (SRW, kg) for the prediction of the composition of empty body gains made by various breeds of sheep and cattle

	Females	Castrates	Males
Sheep			
Merino (small, e.g. Saxon), Southdown	40	48	56
Merino (medium), Hampshire, Polwarth, Dorset x Merino, Ryeland	50	60	70
Border Leicester x Merino, Cheviot, Corriedale, Dorset, Drysdale, Romney, Suffolk, Tukidale	55	66	77
Merino (large, e.g. South Australian), Border Leicester	60	72	84
Cattle			
Jersey	400	480	560
Ayrshire, Guernsey	450	540	630
Beef Shorthorn, Dairy Shorthorn, Devon (Red), Galloway, Red Poll Angus, Hereford	500	600	700
Blonde d'Aquitane, Brahman, Brahman x Hereford, Murray Grey, Limousin, Lincoln Red, Friesian, South Devon	550	660	770
Charolais, Maine Anjou, Simmental	650	780	910
Chianina	700	840	980

Table 1.13. Values for the composition of empty body gain (EBG) at various stages of growth (Z = current weight/SRW) and two rates of gain (R) predicted with set A parameters (in equations 1.30 and 1.31) for immature sheep and cattle other than large lean breeds and with set B parameters for large lean breeds of cattle (see text)

Z	Energy (MJ/kg EBG)				Fat (g/kg EBG)				Protein (g/kg EBG)			
	Set A		Set B		Set A		Set B		Set A		Set B	
	R=0	R=2	R=0	R=2	R=0	R=2	R=0	R=2	R=0	R=2	R=0	R=2
0.06	9.0	10.8	8.6	10.4	112	162	99	149	196	189	198	191
0.08	9.3	11.0	8.8	10.6	120	169	106	154	194	187	197	190
0.10	9.6	11.3	9.0	10.8	128	176	113	161	192	185	195	188
0.15	10.1	12.0	9.7	11.4	153	198	132	178	186	180	190	184
0.20	11.4	12.9	10.5	12.1	182	225	156	199	180	173	184	178
0.25	12.6	14.0	11.5	12.9	216	257	185	224	172	166	177	172
0.30	13.9	15.2	12.6	13.8	256	292	217	253	162	157	169	164
0.35	15.3	16.5	13.7	14.9	299	331	252	284	152	148	161	156
0.40	16.9	17.9	15.0	16.0	344	372	288	316	142	138	152	148
0.45	18.7	19.2	16.2	17.0	388	412	324	348	132	128	143	140
0.50	19.8	20.5	17.4	18.1	431	451	359	379	122	119	135	132
0.55	21.1	21.7	18.4	19.0	470	486	391	408	112	110	127	124
0.60	22.3	22.8	19.4	19.8	505	517	420	433	104	103	120	118
0.65	23.3	23.7	20.2	20.6	534	545	444	454	98	96	114	112
0.70	24.1	24.4	20.9	21.1	559	567	463	471	92	91	109	108
0.75	24.8	25.0	21.4	21.6	578	585	480	486	87	86	105	104
0.80	25.3	25.5	21.8	22.0	594	599	492	497	84	83	102	101
0.90	26.0	26.1	22.4	22.5	616	618	510	512	79	78	98	97
1.00	26.5	26.5	22.8	22.8	629	629	520	521	76	76	95	95

Oddy and Sainz (2002) conclude that a growth check before the young animal has reached 40% of its mature weight (i.e. $Z = 0.4$) will reduce its long-term capacity to grow muscle and bone whereas above this point, compensation will usually be complete. In the former case, recovery predisposes to greater fatness whereas recovery after 40% maturity will initially favour lean-tissue growth at the expense of fat deposition.

Prediction of the composition of gain in mature animals

Wright and Russel (1984*b*), Sanson *et al.* (1993) and Williams and Jenkins (1997) have shown that the energy value of weight change in mature sheep and cattle varies directly with the relative body condition of the animal, i.e. its live weight as a proportion, BC, of its SRW (see Chapter 6). Grainger and McGowan (1982) and Robinson (1987) have shown similar relationships in dairy cows and ewes mobilising body tissue during lactation. The following equations, based on the results of Wright and Russel (1984*b*) have been **adopted** in this Report for both sheep and cattle.

$$\text{Energy (MJ/kg EBG)} = a + 13.8\ \text{BC} \quad (1.32)$$

$$\text{Fat (g/kg EBG)} = b + 420\ \text{BC} \quad (1.33)$$

$$\text{Protein (g/kg EBG)} = c - 115\ \text{BC} \quad (1.34)$$

where:

$a = 13.2$ for **A** type animals; 9.4 for **B** type cattle,

$b = 224$ for **A** type animals; 113 for **B** type cattle,

$c = 187$ for **A** type animals; 207 for **B** type cattle.

These equations can also be expressed as functions of the condition score, CS, of the animal, according to the conventions set out on p. 52.

$$\text{Energy (MJ/kg EBG)} = a + b\ \text{CS} \quad (1.32A)$$

$$\text{Fat (g/kg EBG)} = c + d\ \text{CS} \quad (1.33A)$$

$$\text{Protein (g/kg EBG)} = e - f\ \text{CS} \quad (1.34A)$$

with the coefficients listed below:

CS system	**Animal types**	*a*	*b*	*c*	*d*	*e*	*f*
5 unit range	**A** type animals	20.8	2.07	455	63	124	17.3
	B type beef cattle	17.0	2.07	344	63	144	17.3
8 unit range	Dairy cattle	21.4	1.24	474	38	119	10.4

Liveweight loss

Searle *et al.* (1972) concluded that the composition and energy value of liveweight loss in a sheep of any given type and live weight is similar to that of its liveweight gain. Studies by Blaxter *et al.* (1982) give support to this view, which may also be taken to be valid for cattle. Consequently the energy provided to animals from catabolism of their tissues may be calculated by means similar to those used to calculate the energy content of gains (that is, by 'reverse use' of equations 1.30 and 1.32). The efficiency of use of this energy for maintenance, discussed on p. 21, is assumed to be 0.80.

Liveweight change during lactation

In lactating cows, energy from body tissues is often utilised for milk synthesis, especially during the weeks immediately after calving (Flatt *et al.* 1969), but at this time it is particularly difficult

to determine what fraction of an observed liveweight change (LWC) is actually due to a change in gut fill or other changes in the water content of the body. Beever *et al.* (2001) found that although high-yielding dairy cows maintained live weight after five weeks of lactation, they were still in negative energy balance at 20 weeks. Increases in the water content of the body during this time would explain the estimates of 40 to 100 MJ/kg liveweight loss in grazing ewes by Geenty and Sykes (1986); energy estimates that far exceed any possible combination of fat and protein.

It is suggested that changes in the energy reserves of lactating animals may be more accurately assessed from their condition score, using equation 1.32A, rather than from measurements of LWC. For example, a decrease in CS from six to five in a lactating dairy cow of SRW 500 kg may be associated with a loss of $45 \times 28.8 = 1296$ MJ; the same animal may be losing little or no live weight.

The efficiency of use for milk production of energy from mobilised body tissues is discussed on p. 50, and the efficiency with which dietary ME is used by lactating cows for LWC is discussed on p. 45.

Efficiency of use of ME for weight gain (k_g)

There is general agreement that the net efficiency of use of ME for protein deposition (MJ protein per MJ of ME = k_P) is lower than for fat deposition (k_f); it is also more variable. The majority of studies has been made with non-ruminant animals. For example, efficiencies in rats of approximately $k_P = 0.45$ and $k_f = 0.75$ were reported by Pullar and Webster (1977) but because the heats of combustion of protein and fat are 23.6 and 39.3 kJ/g respectively, the ME requirements per unit of mass deposited in both instances were about 53 MJ/g (i.e. $23.6/0.45 \approx 39.3/0.75 \approx 53$). However, in ruminants, Owens *et al.* (1995) have reported that k_p is even lower, at 0.2. The variability in k_p reflects variation in the relative rates of protein synthesis and degradation, protein deposition being the net outcome from these two variables in protein turnover in the body (see Oddy and Sainz 2002).

The deposition of 1 g protein in body tissues is associated with an accretion of 3–4 g water, whereas adipose tissue contains very little water. Consequently if a given quantity of ME is used exclusively in protein synthesis, this will be manifest as a gain in EBW (or live weight) that is 5–6 times greater than when the same quantity of ME is used exclusively for fat deposition.

The use of the single term k_g to describe the efficiency of use of ME for both protein and fat deposition introduces some imprecision in estimates of actual energy gains. Use of any given value for k_g will tend to overestimate energy gains when a high proportion is in the form of protein because k_p is less than k_f. In these circumstances the k_g value might be discounted, but incremented for principally fat gain. Blaxter *et al.* (1966*a*) found no change in k_g with age in cattle, but Graham (1980) found that with sheep, k_g increased from 0.52 ± 0.02 in weaned lambs two months old to 0.55 ± 0.02 for a similar diet given to the same sheep when 10 months old, and that subsequently it did not vary at ages up to six years. Other evidence has been reviewed by Vermorel and Bickel (1980), and studies with Hereford and Holstein steers (Garrett 1971) and with female and entire male cattle indicate that k_g increased with the proportion of fat in the gain.

There is no serviceable alternative to the use of the single term k_g to describe the efficiency of ME use for growth, particularly because of lack of definition in practice of how k_p varies with physiological state and feeding level, and with feed quality (i.e. variation in the spectrum of

nitrogenous and other nutrients absorbed by an animal). Measurements of k_g have been made with animals that would have shown variation in composition of gain, and so there will be some inherent allowance in predicted k_g for this variation. A more direct allowance would be preferable, but possible procedures are too uncertain for practical use and unlikely to be an improvement on the k_g predicted for any given class of feed from its M/D.

Milk diets

A number of estimates reviewed by ARC (1980) showed little variation about a mean value of k_g for milk and milk substitute feeds of 0.70.

Prediction of k_g

AFRC (1993) proposed the use of a single function ($0.78q_m + 0.006$) for the net efficiency of utilisation of ME for growth and fattening (k_g) for all diets.

This equation in terms of M/D is:

$$k_g = 0.042\ M/D + 0.006 \tag{1.35}$$

A simpler expression yields essentially the same values for k_g and this equation is **adopted** in this Report for all concentrate feeds and conserved forages:

$$k_g = 0.043\ M/D \tag{1.36}$$

Equation 1.35 was derived from studies on a wide variety of feeds, including 'first growth' forages and 'aftermath' forages, for which ARC (1980) gave separate equations. In Europe, the values of k_g for aftermath or autumn growths are much lower than for spring growths of similar M/D (Corbett *et al.* 1966; Blaxter *et al.* 1971). This difference is unimportant when the feeds are components of mixed diets, but it is important when they are fed alone or grazed. The first cause of reduced NE value is probably a reduction in the net efficiency of microbial fermentation in the rumen, which yields to the animal, from a given intake, lesser amounts of metabolites. For autumn compared with spring grass, Beever *et al.* (1978) reported lesser yields of short-chain fatty acids (SCFA) per mole of substrate fermented, and Ribeiro *et al.* (1981) reported lesser amounts of amino adds entering the small intestine, and absorbed, per unit ME intake.

There is also a change in the composition of the SCFA, particularly an increase in the proportion of acetic acid and a decrease in propionic acid (Corbett *et al.* 1966), probably reflecting a decrease in the readily fermentable (water-soluble) carbohydrate content of the forage (Dove and Milne 1994). This change in SCFA will probably reduce efficiency of use by the animal (Hovell *et al.* 1976). Utilisation of absorbed acetate for synthesis of long-chain fatty acids that can be stored in the body is dependent on a supply of NADPH and glycerol phosphate (GP). Propionate is a major precursor of glucose, which provides NADPH and GP in adipose tissue and a reduction in the propionate supply will tend to result in wasteful oxidation of a larger proportion of the acetate supply and a reduction in the proportion used for lipogenesis (Lobley 1986). Amino acids may also be used for gluconeogenesis and a decrease in the supply relative to ME may be a contributory cause of the reduction in the NE value of pasture as the season advances. These arguments are supported by observations that k_g is not reduced when late-season grass is included in mixed diets with cereals or other feeds that can be expected to yield substantial amounts of propionate and other gluconeogenic products of digestion.

There is little information on the NE value of tropical forages, but it is known (Norton 1982) that they characteristically contain lesser concentrations of soluble non-structural carbohydrates

than temperate forages, and greater concentrations of structural, cell-wall carbohydrates, with the result that there are higher proportions of acetate in the ruminal SCFA. However, attempts to measure k_g have given very variable results, partly because of the low rates of gain achieved on the experimental diets (Rees *et al.* 1980; Tudor and Minson 1982).

From this evidence it is concluded that for grazed temperate pasture, it is preferable to use an alternative procedure (adapted from Freer *et al.* 1997), which is derived from equation 1.36 and

(*i*) describes for any given M/D a cyclical variation with season in k_g; and

(*ii*) allows that, at a given M/D, the value of k_g will vary directly with the proportion of legume relative to grass (Freer and Jones 1984). A range of typical predicted values is illustrated in Fig. 1.10.

$$k_g = 0.035 \text{ M/D } (1 + 0.33 \text{ Le}) (1.0 + 0.12(\lambda \sin(0.0172T)/40)) \quad (1.37)$$

where:

Le = the proportion of legume in the forage,

T = the day of the year from 1 January,

λ = the latitude (°) of the site; negative in the south.

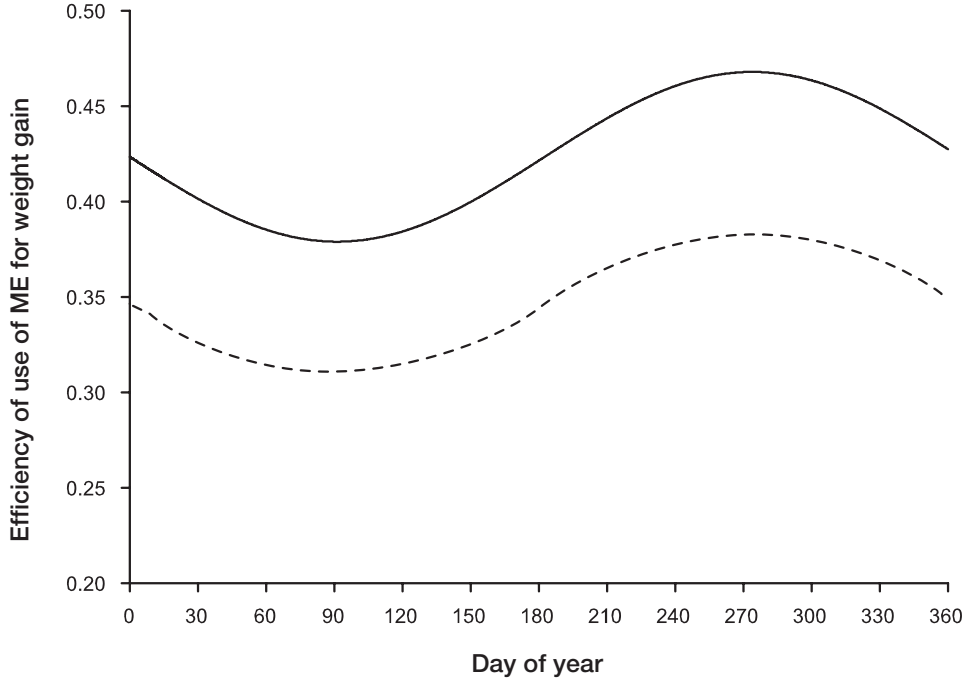

Fig. 1.6. The efficiency of use of metabolisable energy for weight gain in relation to herbage metabolisability, M/D, and time of year for a pasture containing 30% legume and at a latitude of 35°S. Solid line, M/D = 11; dashed line, M/D = 9.

There is little information on how much supplement would have to be given to grazing animals to affect the efficiency of use of the pasture. In default, it is suggested equation 1.36 be applied to the supplement portion of the ME intake, and that equation 1.37 (or failing that, 1.36) be applied to the predicted pasture ME intake. As seasonal effects are less at lower latitudes and less information is available, it is suggested that equation 1.36 be used for grazed tropical pasture.

It is again emphasised that with the use of equation 1.19 and 1.20, the value of k_g for any particular feed is not to be varied with level of feeding.

Table 1.14. Examples of ME requirements for maintenance and gain in housed growing animals and of gain expected from a predicted ME intake at pasture

	Hereford steer	Castrate Dorset sheep
Housed, and given feed with M/D 11		
Age (years)	1	0.5
Standard Reference W (kg) (Table 1.12)	660	66
Current W (kg) (Z = 0.45)	300	30
Rate of gain: live weight, kg/d	1.0	0.2
k_m (equation 1.21)	0.72	0.72
k_g (equation 1.36)	0.47	0.47
ME_m (equation 1.19): Basal	38	4.8
$0.1ME_p$	4	0.7
Total	42	5.7
ME for gain (ME_P)	35	7.9
Total ME (MJ/d)	77	13.6
Other estimates:		
AFRC (1993)	79[A]	11.7[B]
Grazing pasture[C]		
Diet DMD	0.70	0.70
M/D (equation 1.12A)	10.0	9.9
DMI, kg/d (Ch. 6)	8.2	1.36
MEI, MJ/d	81	13.5
k_m (equation 1.21)	0.70	0.70
ME_m (equation 1.20): Basal	36	4.6
0.09MEI	7	1.2
ME_{graze}	6	0.8
Total	49	6.6
Spring		
k_g (equation 1.37)	0.42	0.42
NE gain MJ/d[D]	13.6	2.60
Liveweight gain g/d	820	149
Autumn		
k_g (equation 1.37)	0.34	0.34
NE gain MJ/d[D]	11.1	2.09
Liveweight gain g/d	670	120

[A] Castrate cattle of a medium maturing breed.

[B] Non-Merino castrate lambs.

[C] Age, SRW and current W the same as for the housed steer and wether, and E_{cold} = 0; herbage (2.5 t DM/ha and 1.5 t DM/ha for cattle and sheep, respectively) consists of temperate grasses and 30% clover, grown at latitude 35°S, with undulating terrain.

[D] NE gain = k_g (MEI – ME_m) (for sheep, ME for wool production is also deducted from MEI).

Liveweight gain during lactation

Several studies have shown that when lactating cows are in positive energy balance the efficiency of conversion of ME to body tissue gain is considerably greater than in non-lactating animals. Moe *et al.* (1970) found that the efficiency of energy deposition in lactating cows was as high as the efficiency of use for milk production. This is the view of MAFF (1984*a*) that uses the value 0.62 for both ME conversion efficiencies. The ARC (1980) predicts k_g for energy storage during lactation as 0.95 k_l, where k_l is the net efficiency of use of ME for milk production (see p. 47). In this report a general value of 0.60 for efficiency of conversion of ME to gain is **adopted** for lactating cows, ewes and goats.

During the first lactation the skeletal size and W of an animal are likely to be less than those it will eventually attain, and it can be expected there will be some partitioning of energy and nutrients towards body growth. Some allowance for this is inherent in the procedure for predicting feed intake (Chapter 6) because the current W of the animal as a fraction of its SRW (i.e. Z) will be less than for an older animal (but >0.85), and at any given W its predicted intake will be greater. In addition, in predicting the animal's performance, the lactation curve defining potential milk yield would be set lower for first lactation than for subsequent lactations (e.g. Wood 1969), allowing that a greater proportion of the feed intake would be available for growth.

ME requirements for weight gain

Housed animals

Examples of the calculation of ME requirements for maintenance and gain in housed cattle and sheep are shown in Table 1.14 and are compared with estimates from the UK feeding system. For housed, growing cattle, there is little difference between these estimates and those reported by AFRC (1993) but the estimates for growing sheep are about 9% higher, despite the 'inclusion of a 5% safety margin' in the AFRC estimates for all animals.

Grazing animals

Table 1.14 also shows estimates of the liveweight gains made by the steer and wether grazing, on undulating terrain, a pasture with abundant feed (steers 4 t and sheep 2 t GF/ha) of DMD = 0.7, and no cold stress. The DM intakes are predicted as described in Chapter 6. The estimated LWG in both spring and autumn are approximately those often obtained in practice. It will be noted that ME_{graze} is 0.16 (steer) and 0.17 (wether) of the other components of ME_m. Spring herbage with a predicted k_g value of 0.41 resulted in higher LWG than in autumn, the difference amounting to 150 g/d and 36 g/d for the steer and wether, respectively. If the first-growth temperate pasture provided feed with DMD = 0.8 (M/D = 11.6), the predicted performances of the steer (and wether) are DMI of 9 kg/d (1.56 kg/d), and LWG of approximately 1.5 kg/d (320 g/d) that, given such high-quality pasture, could also be obtained.

Energy requirements for wool growth

In nutritional studies of wool growth, emphasis is properly placed on the quantity and quality of the amino acid supply and its use, but there is also an energy requirement.

Paladines *et al.* (1964) reported that the heats of combustion of wool protein (clean fibre) and wool wax were 23.47 and 40.76 kJ/g respectively and these values were adopted by ARC (1980). A number of studies have examined the gross energetic efficiency of wool growth (with

protein non-limiting). In grazing Merino sheep not pregnant or lactating it has generally been in the range of about 8–14 g of clean dry wool per kg DOMI, or about 03–0.9 g/MJ of ME (e.g. Langlands and Hamilton 1969; Langlands and Bennett 1973; Langlands and Bowles 1974). There has been only one estimate of the net efficiency of use of ME for wool growth, by Graham and Searle (1982) who reported k_{wool} of 0.16–0.19 for Corriedale and Dorset Horn wether lambs.

Sheep of wool breeds continue to grow wool even when chronically undernourished, and because of the inevitability of this production its energy cost is often accepted as an integral part of ME_m. Values of k_m determined with sheep describe principally the efficiency with which ME is used to spare body fat and protein from catabolism, but they also include, and will be modified by, the effects of a relatively small k_{wool} component. Similarly, values of k_g describe the efficiency with which ME is used for fat and protein gains in body tissues and concurrently for an undefined growth of the fleece. From information in ARC (1980) it appears that many of the determinations of k_m and k_g have been made with sheep that grew about 6 g dry greasy wool/d, which is 2.2 kg/yr of clean fibre plus wax and suint. The fleece of British breeds of sheep generally contains less wax than that of Merinos, and Kellaway (1973) found the mean heat of combustion of oven-dry greasy wool from crossbred sheep (Dorset Horn × Border Leicester–Merino) was about 22 kJ/g and from Merinos was about 23 kJ/g. The latter value is in reasonable agreement with a calculated value based on: (*i*) data from the Australian Wool Corporation (1986) on the clean scoured yields of the main lines of Merino fleeces free of vegetable fault and excessive dirt, which indicate about 0.60 g clean dry wool per g fleece; (ii) the assumption that wax is about 40% of the loss during scouring of 0.4 g/g greasy fleece; and (iii) the use of caloric values of Paladines *et al.* (1964)

With k_{wool} = (say) 0.18, the ME requirement may be estimated as 0.13 MJ/g dry greasy fleece growth, or about 0.11 MJ/g fleece as shorn. Because k_m and k_g appear to allow for a fleece growth of about 6 g/d, an ME allowance might be made only for fleece growth in excess of this rate, that is:

$$\text{ME for wool (MJ/d)} = 0.13(\text{Fl} - 6) \tag{1.38}$$

where Fl is greasy fleece growth g/d.

This amount of ME will be small in absolute terms and in relation to the total ME intake that would sustain a high fleece growth rate. It will be within the limits of determination of actual feed intakes and M/D, and the values of k_m and k_g that applied, and in practical feeding an ME allowance for wool could be ignored.

Net energy requirements for milk production

Cows

The heat of combustion of cow's milk (E, MJ/kg), which is the NE required for its production, can be predicted with the equation of Tyrrell and Reid (1965):

$$\text{E} = 0.0386\ \text{F} + 0.0205\ \text{SNF} - 0.236 \qquad \text{RSD} \pm 0.037 \tag{1.39}$$

where F and SNF are the fat and solids-not-fat concentrations (g/kg milk).

Clarke and Moate (1988) have pointed out that protein and lactose (P and L, g/kg) as well as F are now commonly determined, allowing use of the equation of Perrin (1958*b*):

$$\text{E} = 0.0381\ \text{F} + 0.0245\ \text{P} + 0.0165\ \text{L} \tag{1.40}$$

When only the fat content of the milk is known, use can be made of the 'fat-corrected milk' (FCM) formula of Gaines and Davidson (1923): FCM = milk kg (0.4 + 0.15 F%). Crovetto and Van

der Honing (1984) examined 612 samples of milk from Jersey and Friesian cows; concentrations of fat per kg milk varied from 20–110 g, of protein from 25–47 g, and of energy from 2.16–6.15 MJ. They reported that overall there was least bias in predicted energy values (mean discrepancies from observed values of +1.97% for Jersey milks and –1.31% for Friesian milks) by assuming 1 kg FCM = 3.054 MJ, or by using the corresponding regression equation: E = 0.0458F + 1.222.

Sheep

The energy value of ewe milk can be predicted with equation 1.40 or that of Brett *et al.* (1972), which was derived from analyses of Merino and Border Leicester milks:

$$E = 0.0328\ F + 0.0025\ D + 2.203 \quad (1.41)$$

where D is day of lactation.

If F is not known, the observations of Peirce (1934, 1936), Moore (1966) and Corbett (1968) indicate 80 g/kg might be assumed, rather than the 70 g/kg of ARC (1980). The higher value will tend to overestimate E for milk from ewes on high grain diets that may reduce F (Oddy 1978), and underestimate E for milk from ewes in later lactation or undernourished, but in all these instances the milk yields will generally be low and the absolute error will be small.

Goats

Morand-Fehr *et al.* (1980) reported that the relationship between the energy of goat milk and its fat content is similar to that for cows, and estimates can be made with equation 1.42 if there is no information on P and L for equation 1.40.

$$E = 0.0492\ F + 1.309 \quad (1.42)$$

Efficiency of use of ME for milk production (k_l)

The net efficiency of use of ME for milk production by cows (k_l) varies directly with the ME concentration in the diet. The ARC (1980) predicts k_l with an equation, which expressed in terms of M/D, is: $k_l = 0.02\ M/D + 0.41$. This gives values that are greater by about 0.02 than those predicted with an equation of Van Es (1978), which in turn may overestimate k_l for pasture-based diets (Van der Honing and Van Es 1983; Trigg *et al.* 1983). The simplified equation 1.43 probably predicts values of k_l that are appropriate in practice and is **adopted** in this Report. In contrast to the prediction of k_g (equation 1.37), there is no evidence that k_l on a pasture diet varies with the time of year and Smith (1988) concluded that there are no indications that it varies directly with the proportion of legume.

$$k_l = 0.02\ M/D + 0.4 \quad (1.43)$$

The k_l obtained for sheep by Vermorel *et al.* (1987) was in agreement with results from dairy cows and, consequently, equation 1.43 can be used for sheep.

Armstrong and Blaxter (1965) reported k_l of 0.65–0.72 for goats given hay and concentrate diets plus intraruminal infusions of SCFA. They noted that a major difficulty in lactation experiments, which applies in all species, is to assess ME being used for maintenance and thence the ME actually being used for the synthesis of milk. There is no reason to suppose equation 1.43 is inappropriate for goats as Sahul *et al.* (2004) reported a mean value of 0.59 for k_l from a wide database.

Following ARC (1980), it is assumed that energy from body tissues is converted to milk energy with an efficiency of 0.84. Use of the same value for sheep is supported by Vermorel *et al.* (1987).

ME requirements for milk production

The maintenance metabolism of lactating animals will vary with feed intake, as it does in those not lactating. Holter (1976) has provided evidence of an increased maintenance metabolism in dairy cows from measurements of FHP/kg $W^{0.75}$, which he found was increased by 4 kJ per kg milk/d produced by the animals immediately before they were fasted. The milk yields varied from 3 to 34 kg/d, and FHP of the more productive cows were 15% greater than those determined with the same cows one month after lactation had ceased. Oddy *et al.* (1984) found that with the onset of lactation in ewes there was an increase in the energy expenditure of non-mammary tissues.

It is concluded that the term 0.1 ME_p from equation 1.19 should be used in calculating ME requirements for milk production, as shown in the examples in Table 1.15 where the inclusions of 14 (housed cow) and 1.1 (housed sheep) MJ/d of ME represent increases in the maintenance metabolism of 25 and 17% respectively. In simulations of growth and production in sheep (Graham *et al.* 1976) and cattle (Graham 1981) allowance has been made for an increase in the maintenance metabolism during lactation of up to 30%. Similarly, the term 0.09 MEI (equation 1.20) is used in the calculations for estimating milk production from a predicted MEI.

Agnew and Yan (2000) and Kebreab *et al.* (2003) have reported that the maintenance energy requirements of dairy cows of high genetic merit, yielding up to 52 kg/d of 4% FCM, are 30% higher than values predicted by AFRC (1993) and suggest that ME_m for such animals should be calculated as 0.63 MJ/kg$W^{0.75}$ rather than 0.48 MJ/kg$W^{0.75}$. Corbett and Freer (2003) showed that there is no need to make a special case for these cows; the additional requirement may be viewed as a consequence of the animals' increased intakes of ME and is accounted for in the terms included in the prediction of ME_m from equation 1.19 or 1.20.

Housed animals

The estimated ME requirement for a 600 kg cow yielding 30 kg milk/d (122 g total solids/kg) is 212 MJ/d (Table 1.15), which is similar to the estimates of MAFF (1984*a*) and AFRC (1993). The MAFF (1984*a*) allowances have been found to give good results in practice, provided account is taken of changes in cow live weight (Broster and Thomas 1981). The estimate of 19 MJ/d for a 50 kg ewe producing 1.5 kg milk/d is slightly greater than those of MAFF (1984*a*) and AFRC (1993) for the production of the same amount of milk with the same energy content by a housed ewe.

Grazing animals

In the estimates of the amounts of milk produced from pasture (Table 1.15) it is assumed that the animals are offered high-quality pasture (DMD of feed eaten = 0.75) on undulating terrain and that the animals are not cold-stressed.

The estimated milk yields are similar to those commonly obtained in practice. The estimated ME_{graze} are about 0.2 of the other two components of ME_m, these higher increments compared with the steer and wether (Table 1.14) reflecting the additional energy expenditure incurred by grazing larger amounts of feed. As discussed earlier (p. 23) ME_{graze} will be lower for strip-grazed dairy cows because of the shorter distance walked during grazing but, for all dairy cows, will be increased for the distance walked to the milking shed.

Table 1.15. Examples of ME requirements for housed lactating animals and of production expected from a predicted ME intake at pasture

	Friesian cow	**Merino ewe** (suckling single lamb)
Housed, feed with M/D 11		
Age (years)	5	4
Standard Reference Weight (kg)	600	50
W (kg)	600	50
Liveweight change	0	0
Milk yield (kg/d)	30	1.5
Fat (g/kg milk)	36	75
Weight gain by lamb (g/d)		245
Day of lactation	60	21
k_m (equation 1.21)	0.72	0.72
k_l (equation 1.44)	0.62	0.62
ME_m (MJ/d) basal	57	6.6
$0.1ME_p$	14	1.1
Total (equation 1.19)	71	7.7
ME required by lamb (MJ/d)		7.4
ME for milk (MJ/d)	141	11.4
Total ME required (MJ/d)	212	19.1
Other estimates		
MAFF (1984)[A]	210	17.4
AFRC (1993)[A]	220	18.0
Grazing pasture[B]		
Diet DMD	0.77	0.77
M/D (equation 1.12A)	11	11
k_m (equation 1.21)	0.72	0.72
k_l (equation 1.44)	0.62	0.62
DMI (kg/d) (Ch. 6)	19.9	1.95
MEI (MJ/d)	223	21.5
Milk (kg/d)	30.0	1.5
Liveweight change (g/d)	–320	7
Weight gain by lamb (g/d)		258
ME_m (MJ/d) basal	53	6.1
ME_{graze}	11[C]	1.1
0.09 MEI	20	1.9
Total (equation 1.20)	84	9.1
ME used for milk production (MJ/d)	149	11.6

[A] Estimates were on feed with D/M = 11.5, and include a 5% safety margin.

[B] Age, live weight, stage of lactation and milk composition the same as for the housed cow and ewe, and $E_{cold} = 0$. Pasture as in Table 1.14, except for DMD.

[C] Does not include energy cost of walking to milking shed.

Liveweight changes during lactation

The quantity of dietary ME equivalent to the energy mobilised from body tissues for milk production, or stored as LWC during lactation can be estimated from equation 1.32A. This indicates that for a lactating dairy cow in CS 4, 1 kg LW change = 26 MJ NE, while for a cow in CS 2 the value is 24 MJ/kg. These are greater than the value adopted for cows by AFRC (1993). Lactating beef cows or ewes would have the same values in corresponding condition. If it is assumed that k_l and k_g during lactation = 0.60; and that the efficiency of conversion of body energy to milk is 0.84, then dietary ME equivalent to:

(a) 1 kg loss in W used for milk production = (26 × 0.84) = 21.8 MJ of milk net energy, equivalent dietary ME = 21.8/0.60 = 36 MJ,

(b) 1 kg LWG during lactation = (26/0.60) = 43 MJ of ME.

It is emphasised that such calculations are not used to pre-determine that a lactating cow (or sheep or goat) shall lose or gain W. They are used as an indication that 1 kg loss represents an ME use for milk production equivalent to dietary MEI plus (as above) 36 MJ, and that with 1 kg gain 43 MJ of dietary ME has been used for the gain and not for milk. These estimates will vary directly with the body condition of the animal (equation 1.32A). The calculations assist interpretation of discrepancies between observed milk yields and those anticipated from the MEI, and facilitate appropriate adjustments to the MEI (see below).

It must also be emphasised that changes in water retention, particularly during early lactation, will often conceal large losses of energy from body tissue (see p. 40) and real changes in body reserves may be better estimated through the animal's condition score.

Responses in milk production to increases in ME intake

It is widely recognised that responses in milk production to incremental increases in energy intake above maintenance are not constant, and that a curve of diminishing returns applies. This is due to the increasing partition of nutrients from milk production to body tissue. Conversely, at low levels of ME intake, milk production may be sustained by the catabolism of body tissue. A major problem is to predict the partition of nutrients and so define characteristics of the curve. Partition is not considered in the major systems currently used elsewhere to calculate nutrient requirements for dairy cows. This is most unfortunate because, as Blaxter (1966) pointed out, prediction of the marginal response to marginal increases in energy is of critical importance in determining the most profitable level of feeding.

The most comprehensive data for determining a response curve appear to be those of Jensen *et al.* (1942), which were based on 396 lactation records from cows at six feeding levels. These records were re-analysed by Hulme *et al.* (1986), yielding the following equation, which they used in the CAMDAIRY model for predicting the performance of dairy herds and formulating least-cost and maximum profit dairy cow rations.

$Y = A(1–R^x) + B$

where:

Y = average yield over the whole lactation (l/day);

A = the milk yield (l/day) at the asymptote when nutrient intake is unlimited;

R = ratio of milk produced from the nth MJ of net energy to that produced from the (n–1)th MJ, i.e. the rate of change in incremental efficiency of milk production as energy intake increases;

x = NE intake above requirements for maintenance and pregnancy (MJ NE/day).

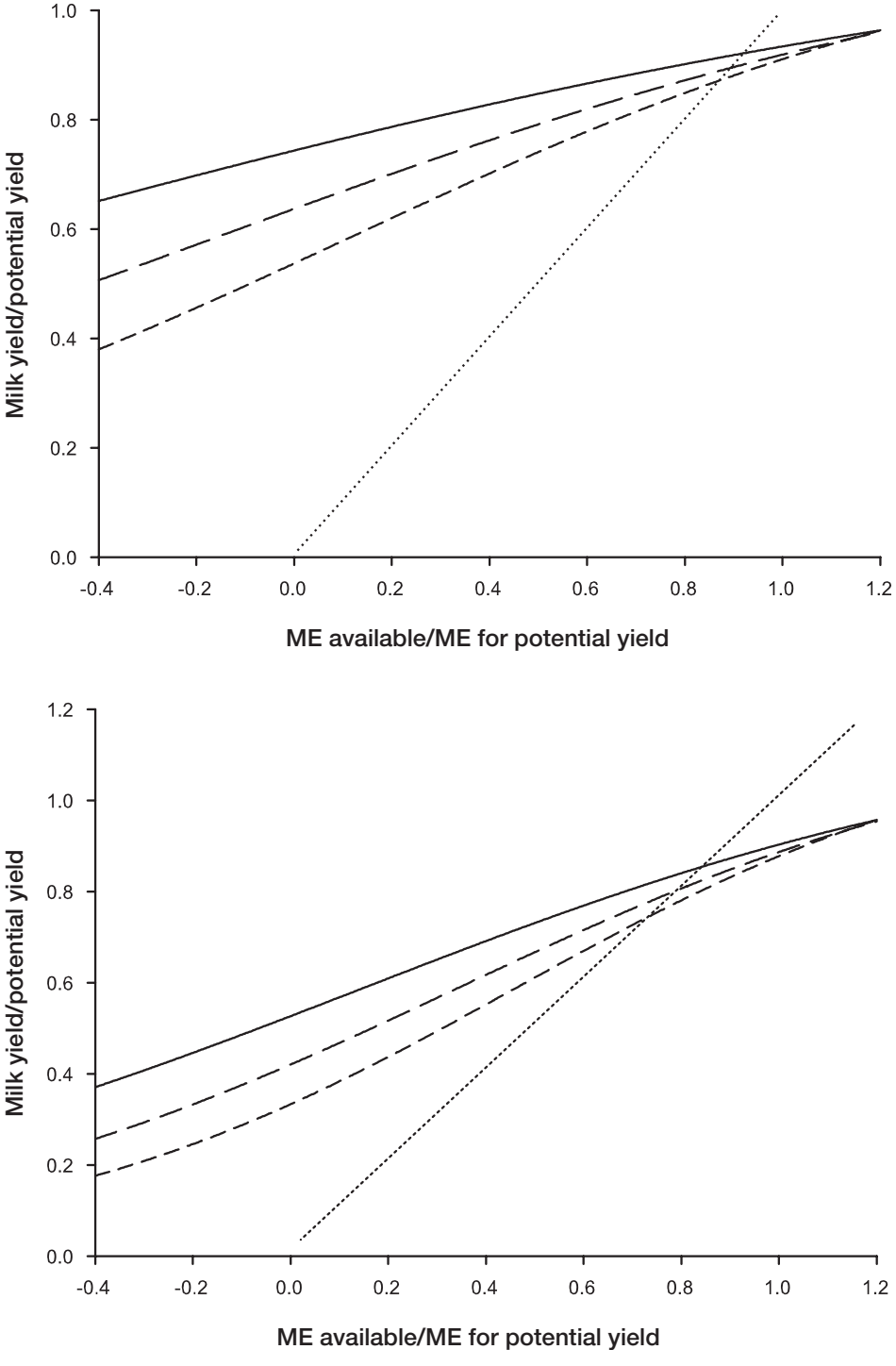

Fig. 1.7. Predicted milk yield, as a proportion of potential yield, in response to available ME intake above maintenance on day 15 (upper graph) and day 90 (lower graph) of lactation, for ewes in relative condition 1.1, 1.0 and 0.9 (from top down), compared with the 1:1 relationship (dotted line).

It was calculated that the ME required per litre of milk for the first 36% of potential milk production was 3.27 MJ; for the next 25%, 6.37 MJ; and then 9.10, 12.52, 17.78 and 28.0 MJ, respectively, for successive intervals of 14%, 10%, 9% and 6% of potential milk production.

As these authors recognised, this equation, which gives a mean yield for the whole lactation, does not take account of the large effects of body condition and stage of lactation on the extent of the partition of nutrients during lactation, so clearly demonstrated by Robinson *et al.* (1999) in the ewe. An important consequence of this, particularly applicable to ewes and beef cows, is that appreciable milk production can be maintained on very low energy intakes for as long as the lactating animal is in good body condition. A more general equation that predicts daily milk-yield response to ME intake in cows and sheep as a function of expected peak yield, stage of lactation, and body condition has been developed by Freer (2002) for use in the GrazFeed decision-support tool (see p. 233). Typical response curves are shown in Fig.1.7.

Generalised computer program for predicting ME requirements

The four examples of ME requirements shown in Tables 1.14 and 1.15 represent isolated points in the almost infinite range of combinations of animal and feed characteristics; a range that is impossible to illustrate adequately in further tables. However, a small spreadsheet computer program (ME Required) is freely available from www.pi.csiro.au/grazplan to enable a user to make the appropriate computation. The user enters values that specify the animals and diet to be tested and the program computes the ME required by the animal, using the same functions that have been presented in this section of the Report.

It is important to recognise that this is the sole function of this program. It does not estimate the voluntary intake of the specified feed, the selection that the animal may be making from the available herbage (or an offered feed) or the partition of nutrients between the competing needs of the animal. Therefore the program cannot be used to predict the productivity that the animal may be able to achieve; only the ME that would be required to achieve a specified level of production. A more comprehensive computer program (GrazFeed) that implements the recommendations in Chapters 1, 2 and 6 of this Report and is designed to predict productivity, particularly for grazing animals, is described on p. 233.

Definition of condition score (CS)

The body reserves of sheep and cattle are often an important source of energy at critical stages of production such as joining, late pregnancy and during lactation. An accurate assessment of the reserves can therefore be an important aid towards optimising nutritional management and reproductive efficiency.

Interpretation of live weights and liveweight changes can be difficult owing to differences in the mature size of animals, stage of pregnancy, and gut fill. This is a particular problem during the early part of lactation, when energy loss from body tissue may greatly exceed apparent weight loss (Beever *et al.* 2001).

The introduction of a system of scoring body condition in sheep by Jefferies (1961) enabled farmers and extension workers to assess body reserves without the need for weighing, and it has been adapted by Lowman *et al.* (1976) for use with beef cattle. It has also been adapted for dairy cattle in Australia by Earle (1976), but using a range in condition scores from 1–8 compared with the range of 0–5 used in sheep and beef cattle. This difference should not cause practical difficulty; for dual-purpose cattle one scale should be chosen and adhered to.

Sheep

The most detailed description of the method for defining condition score (CS) was provided by Russel *et al.* (1969). The prominence of the spinous processes of the anterior lumbar vertebrae is assessed by palpation. The sharpness and degree of cover of the ends of the transverse processes and the extent of the muscular and fatty tissues beneath them are then evaluated by spanning the lumbar vertebrae with fingers and thumb. Appraisal of the depth of the eye muscles (*Mm. longissimus dorsi*) and the degree of subcutaneous fat cover is made by palpating the region between the spinous and transverse processes.

Scores on these bases are as follows:

CS 0: Extremely emaciated and on the point of death.

CS 1: Spinous processes prominent and sharp; transverse processes also sharp, the fingers pass easily under the ends, and it is possible to feel between each process; eye muscle areas shallow with virtually no subcutaneous fat cover.

CS 2: Spinous processes prominent but smooth, and individual processes can be felt only as fine corrugations, transverse processes smooth and rounded, and fingers can be passed under ends with little pressure; eye muscle areas of moderate depth with little subcutaneous fat cover.

CS 3: Spinous processes have only a small elevation, are smooth and rounded, and individual processes can be felt only with pressure; transverse processes smooth and well covered, and firm pressure is required to feel over ends; eye muscle areas full with moderate subcutaneous fat cover.

CS 4: Spinous processes can just be detected with pressure as a hard line between the eye muscles, which are full and have a thick fat cover; the ends of the transverse processes cannot be felt.

CS 5: Spinous processes cannot be felt even with firm pressure and there is a depression in subcutaneous fat where spinous processes would normally be felt; tranverse processes cannot be felt; eye muscle area very full with very thick subcutaneous fat cover; there may be large deposits of fat over rump and tail.

Beef cattle

Lowman *et al.* (1976) provide the following definitions that, in their publication, are illustrated by photographs of representative animals and Scanogram prints taken at the 13th rib.

CS 0: The animal is emaciated with spinous processes, hip bones, tail head and ribs projecting prominently. No fatty tissue can be detected and the neural spines and transverse processes feel very sharp.

CS 1: The individual spinous processes are still fairly sharp to the touch and there is no fat around the tail head. The hip bones, tail head and ribs are still prominent but appear less obvious.

CS 2: The spinous processes can be identified individually when touched, but feel rounded rather than sharp. There is some tissue cover around the tail head, over the hip bones and the flank. Individual ribs are no longer visually obvious.

CS 3: The spinous processes can only be felt with firm pressure. The areas on either side of the tail head now have a degree of fat cover that can easily be felt.

CS 4: Fat cover around the tail head is evident as slight 'rounds' soft to the touch. The spinous

processes cannot be felt even with firm pressure and folds of fat are beginning to develop over the ribs and thighs of the animal.

CS 5: The bone structure is no longer noticeable and the animal presents a 'blocky' appearance. The tail head and hip bones are almost completely buried in fatty tissue and folds of fat are apparent over the ribs and thighs. The spinous processes are completely covered by fat and the animal's mobility is impaired by the large amount of fat carried.

Dairy cattle

The following recommended criteria are illustrated by photographs in the publication by Earle (1976):

CS 1: Emaciated. Very little flesh over the skeleton. Backbone is sharp and is a very prominent ridge. It is very easy to feel individual lumbar vertebrae. The shape of each individual short rib can easily be felt.

CS 2: Very poor. Area around the base of the tail is deeply sunken. Backbone is a prominent ridge. Hips and pins are very prominent. The shapes of the ends of the short ribs can easily be felt. It is easy to feel between the tops of the short ribs.

CS 3: Poor. Area around the base of the tail is sunken. Backbone is a prominent ridge; hips and pins are prominent. The ends of the short ribs can easily be felt. It is possible to feel between the tops of the short ribs with pressure.

CS 4: Light moderate. Area around the base of the tail is only slightly sunken. Backbone is a raised rounded ridge; slight fat covering over pins, hips and short ribs. The ends of the short ribs can be felt and are rounded. It is not possible to feel between the tops of the short ribs.

CS 5: Moderate. Area around the base of the tail is almost filled out. Backbone is a rounded ridge. Even fat covering over pins, hips and short ribs. Only some of the short rib ends can be felt. It is not possible to feel between the tops of the short ribs.

CS 6: Heavy moderate. Area around the base of the tail is filled out. Back is rounded across the loins. Cannot feel the ends of the short ribs or between the tops of the short ribs. Tail head is still prominent.

CS 7: Fat. Back is flat across the loin. Backbone can only be felt by pressing down firmly. Cannot feel short ribs. Hips are well rounded. Tail head is a rounded ridge with some folds of fat either side.

CS 8: Very fat. Backbone is covered by a thick layer of fat and cannot be felt. Cannot feel short ribs. Hips are no longer obvious. Tail head has large folds of fat either side.

Goats

B. A. McGregor (pers. comm.) has successfully used the technique of Jefferies (1961) with Angora and cashmere goats whereas Luginbuhl and Poore (2000) in North Carolina have devised a 1–9 scale for meat goats, adapted from the USA system for beef cattle.

Repeatability of estimates

The repeatability of estimates between observers and by the same observers on different occasions depends on their training and experience. With sheep, Doney and Russel (1968) and Russel *et al.* (1968) found that over a period of three years with six observers the repeatability

within observers was greater than 80%; less than 15% of scores differed by 0.5 and less than 5% by 1.0. There was more than 70% agreement between observers, and scores agreed by two or three observers were more than 90% repeatable. Grainger and McGowan (1982) found that variation within trained observers scoring dairy cattle was similar to that between them, the standard deviation of ± 0.28 units being similar to the level of agreement reported by Macmillan and Bryant (1980). However, when observers not used to working together were tested, Grainger and McGowan (1982) found the s.d. of their scores increased to ± 0.41 units, and in a similar study Evans (1978) found the s.d. between observers was ± 0.36 units.

The visual appraisal of condition score standardised by photographs and written descriptions can be supported by objective measurements of the surface profile around the loins and rump as described by Grainger and McGowan (1982).

Relationships between change in CS and change in live weight and body composition

Sheep (scale 0–5)

Jefferies' (1961) original observations indicated that a change in CS of one unit in strong-wool Merinos and Corriedales corresponded to a change of 7 kg in live weight. This relationship appears to be confirmed for Merinos (represented by Saxon and S. Australian types) by the results of an examination by R. W. Hodge (pers. comm.) of a large number of observations made on several breeds (Table 1.16). The results indicate the equivalence of one unit CS change to 12 kg live weight observed for Scottish Blackface sheep (Russel *et al.* 1969) is also applicable to other British breeds and derivatives of these (e.g. Dorset, Corriedale). Though there is some inconsistency in the results for Polwarth × S. Australian Merino (dry ewes *v.* wethers and weaners), the same equivalence applies also to British breed × Merino crossbreds.

Relationships have been determined between CS and the percentage of fat in the body of sheep by Russel *et al.* (1969), and by R. W. Hodge (pers. comm.). The results in Table 1.17 indicate that one unit increase in CS in Scottish Blackface ewes was equivalent to an increase of about 9% in the fat content of the fleece-free empty body. The corresponding values obtained *in vivo* by reference to tritiated water spaces were 10% for Dorset ewes, and 6–7% for Merinos and Corriedales.

When the Dorset ewes were slaughtered, the energy equivalent of unit CS change was found by R. W. Hodge to be 461 MJ that, as fat (39.3 MJ/kg), is about 11.7 kg and is similar to the value of 11.8 kg W/CS for this breed shown in Table 1.16.

Goats (scale 0–5)

One unit change in CS in Angora wether goats, assessed by Jefferies' (1961) technique (B. A. McGregor pers. comm.) appeared to be equivalent to 6 kg change in W (Table 1.16).

Table 1.16. Regression of live weight (kg) on condition score (scale 0–5) of sheep and goats

Breed, sex and physiological state		n	Intercept	Slope[A]	R^2	RSD
Dry ewes						
Polwarth x SA Merino:	adult[C]	47	33.1	6.3	0.27	4.0
	maiden[C]	60	21.3	7.3	0.28	4.3
Saxon Merino:	adult[C]	44	29.9	5.6	0.29	3.7
	maiden[C]	42	17.6	7.0	0.31	3.0
Scottish Blackface:	adult[B]	30	33.0	10.6	0.76	–
Lactating ewes						
Sth Aust Merino[C]		10	35.3	5.0	0.28	–
Saxon Merino[C]		10	29.4	5.5	0.16	4.3
Corriedale[C]		10	18.9	11.9	0.62	3.6
Dorset[D]		62	20.6	11.8	0.44	8.9
Wethers						
Polwarth x SA Merino[C]		54	18.3	11.8	0.62	6.3
Saxon Merino[C]		58	16.1	10.0	0.70	4.2
Saxon Merino[E]		90	33.2	7.0	0.49	3.9
Weaners						
Polwarth x SA Merino:	wethers[C]	46	5.6	11.3	0.71	3.7
	ewes[C]	45	6.5	10.1	0.62	3.4
Saxon Merino:	wethers[C]	37	7.3	9.3	0.66	3.1
	ewes[C]	42	11.8	7.0	0.52	2.9
Angora goats						
Adult	wethers[E]	90	23.2	6.1	0.60	3.2

[A] Change in live weight (kg) per unit change in CS.

[B] Russel *et al.* (1969).

Analyses by R. W. Hodge of data supplied by:

[C] R. L. Thomson and J. Z. Foot (Pastoral Research Institute, Hamilton, Vic.)

[D] K. G. Geenty and M. Abrahamson (Lincoln College, New Zealand).

[E] B. A. McGregor (Animal Research Institute, Werribee, Vic.)

Table 1.17. Regression of fat percentage in the body of sheep on condition score (scale 0–5)

Breed, sex and physiological state	n	Intercept	Slope[A]	R^2	RSD
Dry ewes					
Scottish Blackface[B]	30	2.7	8.7	0.88	–
Lactating ewes					
Dorset[C]	20	–5.4	10.1	0.64	4.0
Sth Aust Merino[D]	10	2.1	5.8	0.36	3.2
Saxon Merino[D]	10	–1.6	7.0	0.35	3.6
Corriedale[D]	10	–0.3	7.4	0.46	3.7

[A] Change in percent body fat per unit change in CS.

[B] Measurement of fat content made after slaughter of the fleece-free empty body (Russel *et al.* 1969). Fat in the other groups estimated by reference to tritiated water space determined after a 24 h fast and on a fleece-free basis.

Analyses by R.W. Hodge of data supplied by:

[C] K. G. Geenty and M. Abrahamson (Lincoln College, New Zealand). Measurements, after slaughter, of fat in the fleece-free empty body.

[D] J. Z.Foot and R. L. Thomson (Pastoral Research Institute, Hamilton, Vic.). Fat estimated by reference to tritiated water space determined after a 24 h fast, on a fleece-free basis.

Beef cattle (scale 0–5)

Using the CS system of Lowman *et al.* (1976), Wright and Russel (1984*a*) established the regression relationships shown in Table 1.18 for non-lactating, non-pregnant mature cows of several genotypes. On this evidence one unit change in CS in British breeds of beef cattle could be taken as equivalent to about 80 kg W. For Friesian cattle, and for large European breeds (Charolais, Simmental) it is equivalent to at least 100 kg W. There appear to be no observations on *B. indicus* breeds.

Table 1.18. Regression of live weight (kg) on condition score (scale 0–5) of mature non-breeding cows (Wright and Russel, 1984*a*)

Breed	n	Intercept	Slope[A] (± SE)	R^2	RSD
Galloway	15	319	62 ± 9.7	0.75	41.7
Shorthorn x Galloway	14	243	97 ± 10.8	0.87	45.3
Hereford x Friesian	14	239	104 ± 6.3	0.96	25.4
Luing	15	200	106 ± 17.9	0.73	41.8
British Friesian	15	305	110 ± 17.5	0.75	52.2

[A] Change in live weight (kg) per unit change in CS over the range 0.75–4.5.

By slaughter of cows of the five breeds listed in Table 1.18, Wright and Russel (1984*a*) determined the relationships between CS and the composition of the empty body. The change in energy content per unit change in CS was 3478 MJ for the Friesians (CS range 0.75–3.5, mean 2.3 on the 5 point scale) and 2242 MJ/CS for the other four breeds (CS range 1.0–4.5, mean 2.6). With, respectively, 110 and 100 kg W/CS the corresponding changes per kg EB are 31.6 and 22.4 MJ. From further study of their data, Wright and Russel (1984*b*) reported that for all five breeds the energy contents of 1 kg EB change at 300, 400, 500 and 600 kg EBW were respectively 22.5, 25.9, 29.3 and 32.7 MJ. The latter two values, and that derived above for Friesians, are considerably higher than any shown in Table 1.13, but the animals were 'mature'; it could be expected that changes would occur mainly in their fat content, as was observed (700–800 g fat/kg EB change, and less than 70 g protein/kg).

Dairy cattle (scale 1–8)

Using the CS method of Earle (1976), Grainger and McGowan (1982) found that the liveweight change equivalent of one unit change in CS in dairy cattle varied from 17–40 kg. Some of the variation was associated with differences in breed and mature size, and Grainger *et al.* (1982) found the following CS:W equivalents:

Jersey: 26 kg/CS
Friesian × Jersey: 34 kg/CS
Friesian: 42 kg/CS

Gray *et al.* (1981) also studied Friesian, Jersey and Friesian × Jersey cows but not in sufficient numbers to be able to separate breed effects. Their mean result of 36 kg/CS is, however, in good agreement with the average for the breeds above of 34 kg/CS.

A. Hodge (pers. comm.) re-examined the data of Gray *et al.* (1981) and found that an increase from CS3 to CS6 in pregnant Friesian × Jersey cows was accompanied by an increase in the fat

content of the empty body from 7–20%. The fat content of the gain from CS3 to CS4 was 39%, from CS4 to CS5 was 47%, and from CS5 to CS6 was 55%. The energy contents of these empty body gains were respectively 19.4, 21.8 and 24.4 MJ/kg, the increase with CS (i.e. with W) being consistent with expectation (Table 1.13).

The prediction of the composition (energy, fat and protein) of weight change at any specified condition score was discussed earlier (equations 1.32A–1.34A).

Standard reference weight as a scalar of the relationship

Typical values for Standard Reference Weight of cattle and sheep are given in Table 1.12. When CS is defined on a scale of 0–5 (sheep, goats, beef cattle), the prediction of the change in live weight (kg) per unit change in CS as 0.15 SRW yields values that are reasonably consistent with the observations reviewed above. For example, for a fine wool Merino wether with SRW = 50 kg, one unit change in CS is equivalent to 7.5 kg; for a 500 kg Hereford cow, one unit of CS = 75 kg.

For dairy cattle, with a CS scale of 1–8, liveweight change per unit CS may be calculated as 0.09 SRW. Thus for a 550 kg SRW Friesian cow it is 49 kg, and for a 400 kg Jersey cow is 36 kg.

Relationships between CS and production

A number of advisory publications specify 'target' condition scores that should be achieved at particular stages of the production cycle. For example, Lowman *et al.* (1976) recommend a CS of 2.5 for beef cows to be mated in the autumn, and of 2 for mating in the spring when it can be expected that cows will have a high intake of good-quality pasture. In practice, and especially in pastoral production, it may be undesirable or impossible to achieve particular CS. When ewes are to be joined, for example, there may be insufficient feed to bring them to the 'target' or to do so without depriving other stock. Promotion of a higher ovulation rate might result in demands for feed in later pregnancy or after lambing that exceeded the supply available from the pastures.

This section presents information available at present on relationships between CS and animal performance so that, with the information set out above on the ME required to change CS, it can be assessed what changes in nutritional management to alter CS might be appropriate in the conditions prevailing. It should be understood that although CS of individual animals are estimated, the corresponding animal performance can only be predicted on a flock or herd basis and not for the individual.

Sheep (scale 0–5)

Morley *et al.* (1978) analysed the relationships between the live weights of South Australian Merino, Border Leicester × Merino, and Corriedale ewes and their ovulation rates from a number of experiments. For ewes mated in the autumn, when ovarian activity is below maximum, the results shown in Table 1.19 indicate that a unit increase in CS would increase ovulation rate by about 15%, leading to an increase of about 13% in the lambs born per ewe. This is a smaller increase than the 56% observed by Gunn and Doney (1975) with Scottish Blackface ewes. Pollott and Kilkenny (1976) examined data from a large number of British breed flocks and found that one unit increment in CS at joining was associated with a 29% increase in lambs born.

Table 1.19. Ovulation rate during autumn in Border Leicester x Merino (BLxM), South Australian Merino (SAM) and Corriedale ewes as defined by Morley *et al.* (1978) and of Scottish Blackface (SB) ewes (Gunn and Doney 1975) in relation to condition score (CS, scale 0–5)

Live weight	Approx.	Ovulation rate			Ovulation rate	
(kg)	CS	BLxM	SAM	Corriedale	CS	SB
40	1.1	1.3 (1.1)[A]	1.1	1.2	1.5	1.09
50	2.7	1.5 (1.2)	1.3	1.4	2.5	1.60
60	4.3	1.7 (1.3)	1.6	1.7	3.0	1.93

[A] Ovulation rates in summer (December).

Beef cattle (scale 0–5)

Reports by Croxton and Stollard (1976) and Lowman *et al.* (1976) are in agreement with J. F. Graham (1982) who found that the post-partum anoestrus interval (PPAI) in Hereford cows decreased with an increase in CS (Table 1.20). There was no effect on pregnancy rate, although it has been reported that this tends to increase as PPAI lengthens (e.g. Lowman *et al.* 1976). However, Morley *et al.* (1976), from an analysis of results for groups of mature Angus cows grazing at different stocking rates, found an increase in the probability of pregnancy with mean weight at joining that amounted to 0.14 per unit of CS. Responses to CS are even more marked in extensive beef herds in north-western Australia (O'Rourke *et al.* 1991).

Graham and Clarke (1984) showed that CS is a good indicator of fat depth on live cattle, and therefore a useful aid in sales-by-description of animals for slaughter.

Table 1.20. Relationship between condition score (scale 0–5) of grazing Hereford cows at calving and the post-partum anoestrus interval (PPAI)[A]

Condition score at calving	Herbage availability after calving[B]	PPAI (days)	
1.5–2.0	Low	65	(58)[C]
	High	51	
2.5–3.0	Low	45	(41)[C]
	High	37	
3.5–4.0	Low	45	(36)[C]
	High	31	

[A] J. F. Graham (1982). Means from observations in two years.
[B] Low availability approximately 1 tonne DM/ha; high availability approximately 1.5 t DM/ha.
[C] Mean PPAI.

Dairy cattle (scale 1–8)

P. J. Moate (pers. comm.) estimated the CS of 1100 Jersey, Friesian and Jersey × Friesian cows in early lactation and found that the percent calving to first service increased from 50.2 at a mean CS of 2.9 to 56.6 at CS 3.5, and increased further to 64.9 at CS 4.2

Grainger *et al.* (1982) managed cows of the same breeds so that they had a CS of 3, 4, 5 or 6 at calving and during the first few weeks of lactation had mean intakes of ryegrass/clover pasture of either 14 or 8 kg DM/d with a digestibility of approximately 0.7. Post-partum anoestrus interval was longer with the lower than the higher intake, but with both treatments it decreased by six days for each unit increase in CS (Table 1.21).

In the same study, both higher CS (range 3–6) at calving and the higher DM intake had positive effects on the yield of milk, milk fat and milk protein during the five weeks of different intakes. During the first 20 weeks of lactation the initial CS continued to affect fat percentage (Table 1.22) but not protein percentage.

Table 1.21. Relationship between condition score (CS, scale 1–8) at calving and post-partum anoestrus interval (PPAI) in grazing dairy cows with two rates of dry matter intake (DMI) during the first five weeks of lactation (Grainger *et al.* 1982)

CS at calving	Mean DMI (kg/d)	PPAI (d)	
3	8	54	(51)[A]
	14	47	
4	8	48	(45)[A]
	14	41	
5	8	42	(39)[A]
	14	35	
6	8	36	(33)[A]
	14	30	

[A] Mean PPAI.

Table 1.22. Response in milk production per unit increase in condition score (CS, scale1–8) at calving (Grainger *et al.* 1982)

	Period of lactation (weeks)	
	0–5	0–20
Milk yield (litres/CS)	45	130
Fat yield (kg/CS)	5	10
Fat percent (% units/CS)	0.40	0.15

Rogers *et al.* (1979) found it was CS at calving as such that affected subsequent production, and not the preceding rate of change in W that resulted in a given CS.

Loss of condition during lactation (Grainger *et al.* 1982) increased with an increase in initial CS, but after 20 weeks an original one unit CS advantage with cows that had been eating 14 kg DM/d still resulted in a CS higher by 0.24 units. It also gave an increase in milk fat production over the 20 weeks of 8.5 kg, and it was calculated that this was equivalent to a return of 1 kg fat for each 24.4 kg of the feed DM that had been provided before calving to increase CS. With cows at the lower level of feeding after calving there was a return of 1 kg milk fat for each 27.2 kg DM previously used to increase CS.

The extra feed after calving, 14 *v.* 8 kg DMI/d, which was 210 kg DM over the five weeks, resulted in 1 kg extra milk fat from about 15 kg DM and this return was not significantly affected by CS at calving.

As discussed earlier (p. 41), CS may give a much better indication, particularly during early lactation, of the energy status of the cow or ewe than is provided by changes in live weight.

Relationships between CS and ME requirements

Maintenance

Procedures for calculating the maintenance requirements of animals (kJ/kg $W^{0.75}$) take no account of variation in their degree of fatness as such and, as discussed on p. 16, ME_m could be

expected to vary between animals kept at different CS only so far as they differed in actual live weight. Despite the conflicting views discussed earlier, it is concluded that, in practice, ME_m should be calculated with equation 1.19 or 1.20 and should not be varied with CS.

Change in condition score

The approximate quantities of ME in addition to ME_m required to increase CS by one unit in mature animals can be calculated from information on kg W/CS and assigning a value to the energy content of the gain (MJ/kg W). Inevitably the precision of both assumptions will be low. Those made in Table 1.23 are derived from the estimates of kg W/CS based on SRW, and of approximate energy gains by reference to equation 1.32A (after adjusting from EBG to LWG). It has also been assumed that M/D = 10, a feed quality that would allow a reasonable rate of increase in body condition, and so k_g has a value of 0.43 (equation 1.36) for non-lactating animals or 0.60 for those lactating.

Table 1.23. Estimates of the quantities of ME (MJ), in addition to ME for maintenance, required to increase condition score (CS) by one unit for lactating and non-lactating animals of different SRW, at different levels of CS; diet M/D = 10

	SRW (kg)	**LWG (kg/CS)**	**Energy change (MJ/kg LWG)**		**ME required[A] (MJ/CS)**			
					Not lactating		Lactating	
			CS=2	CS=4	CS=2	CS=4	CS=2	CS=4
Sheep	40	6	23	27	320	375	230	270
(CS = 0–5)	60	9	23	27	480	565	345	405
Beef cattle	400	60	23	27	3210	3765	2300	2700
(CS = 0–5)	600	90	23	27	4815	5650	3450	4500
			CS=4	CS=6	CS=4	CS=6	CS=4	CS=6
Dairy cattle	400	32	24	26	1790	1935	1280	1390
(CS = 1–8)	600	48	24	26	2680	2902	1920	2080

[A] k_g = 0.43 for non-lactating animals and 0.60 for lactating animals.

In all instances it should be understood that a pasture would not promote a rapid increase in CS unless, in addition to appropriate M/D, the quantity of herbage available (kg DM/ha) were also sufficient to allow the animals to achieve the necessary higher intake (see Chapter 6) compared with animals that are simply required to maintain body condition.

Appendix 1A

Derivation of the generalised equations 1.19 and 1.20 to predict ME requirements for maintenance

The basic equation of Graham *et al.* (1974) after revision of the effect of age was:

$$\text{FHP (MJ/d)} = 0.244\ \text{FW}^{0.75} \exp(-0.03\text{A}) + 2.8\text{G} + 0.046\ \text{DE}$$

For practical application, the equation should predict requirements for live weight (W) maintenance, and the ARC (1980) relationships FW (ruminant diets) = $(\text{W}/1.08)^{0.75}$ and FW (milk-fed animals) = $(\text{W}/1.05)^{0.75}$ have been adopted. Only the first term in the basic equation is weight-dependent and is to be divided by $(1.08 \text{ or } 1.05)^{0.75} = 1.06$ or 1.04.

To allow valid use of ARC (1980) values for k_m:

(*i*) The minimal ME requirement for maintenance (ME_m) is defined as FM/k_m, and it has been assumed that the urinary loss of energy during fast is 0.08 FHP; hence FM = 1.08 FHP. The ARC (1980) equate FM with zero ME intake, and k_m is the efficiency with which feed ME is used, from this basis, to spare body fat and protein from use as a source of energy. Consequently the basic equation has simply to be multiplied by 1.08*.

(*ii*) The equation must predict FM equivalent to those determined with animals that have been held at approximately the maintenance level of feeding before fast. Therefore, with a maintenance intake of DE (MJ/d), which is equivalent to a smaller quantity of ME (= 0.81 DE), the term (0.046×1.08)DE is written as $(0.057 \times 1.08)ME_m$ and is equated with FM. Its effect on the ME requirement for maintenance is $(0.062/k_m)ME_m$ and with $k_m = 0.75$, which is approximately the value observed in the original studies, the term resolves to 0.083 ME_m.

Hence, with liveweight gain zero (i.e. G = 0):

$$FM/k_m = ME_m(\text{MJ/d}) = (yW^{0.75} \exp(-0.03A))/k_m + 0.083\ ME_m$$

where: $y = (1.08/1.06)0.244 = 0.249$; or $y = (1.08/1.04)0.244 = 0.253$

so that, rounding up:

$$ME_m(\text{MJ/d}) = (0.28W^{0.75} \exp(-0.03A))/k_m \qquad (1A.1)$$

and this expression is to be multiplied by the appropriate values for K, S and M as defined in the text.

The effect of liveweight gain, as described in the basic equation, is to increase FHP by 2.8 MJ/kg gain, and with the conversion to predict FM the term becomes 3.02 G. Graham *et al.* (1974) indicated that factor M (see equations 1.19 and 1.20) should be applied to this term and, in tentatively proposing extension to cattle, that K (and by implication S) should also be applied. This apparent effect of rate of growth on non-productive expenditure can be regarded as representing an increase in body protein turnover, and in consequent energy costs, associated with an increase in the rates of synthesis and deposition of protein. To the extent that this is true, the broad similarity between sheep and cattle in the proportion of protein in their empty body gains, and the extent of variation with sex (S) or age (i.e. with M), as shown in Tables 1.8 and 1.23 of ARC (1980), indicate that application of the factors K, S and M is not warranted.

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* Strictly (see p. 3), FM (= FHP + X kJ urine energy) should be equated with an ME intake of –X kJ, when the multiplier would be $[(1.08\ \text{FHP}/k_m) - 0.08\ \text{FHP}]$, but the ARC (1980) convention has been followed.

(i) Equation 1.19

The increase in the maintenance metabolism resulting from G, in NE terms, may be written as 3.02 (ME_P. k_g)/EG where ME_p is the dietary ME used directly for the gain and EG is the energy content of the gain (MJ/kg).

This term divided by k_m expresses the effect on the maintenance metabolism in terms of ME. With $k_g = 0.5$, EG = 20 and $k_m = 0.75$, which are approximately the values observed in the original studies, it resolves to 0.10 ME_P.

(ii) Equation 1.20

The effect on the maintenance metabolism may be written, alternatively, as:

$$[3.02(MEI–ME_m)k_g]/EG.k_m = (0.101\ MEI – 0.101ME_m)$$

where: MEI is the total ME intake and, as before, $k_g = 0.5$, EG = 20, and $k_m = 0.75$.

Equation 1A.1 with this addition and with rounding resolves to:

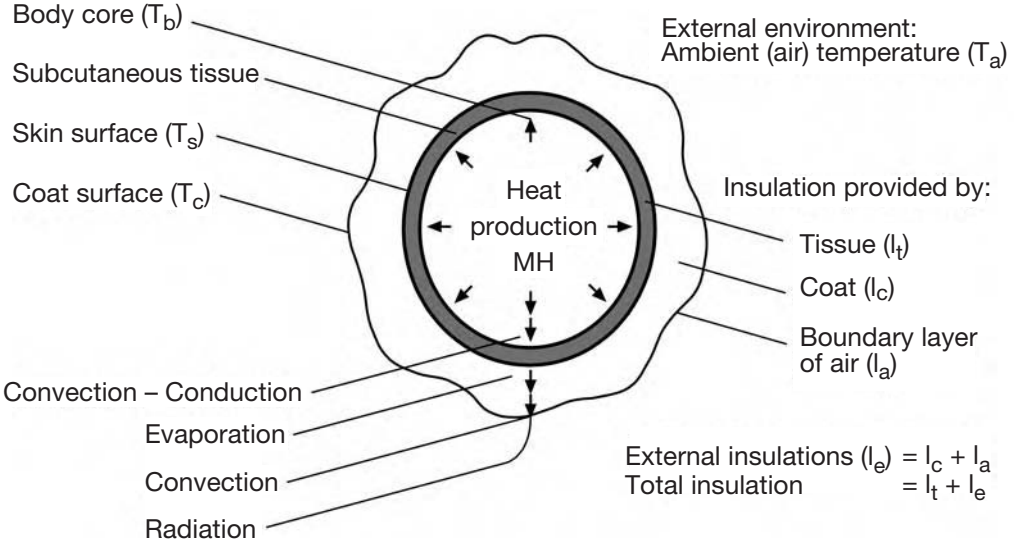
$$ME_m = (0.26W^{0.75} \exp(–0.03A))/k_m + 0.09\ MEI$$

The first term only is multiplied by the appropriate values for K, S and M.

Appendix 1B

Equations for the calculation of E_{cold}

The following diagram illustrates a number of features of thermal loss by the animal to its environment. In cold, with T_a below the animal's lower critical temperature (T_{lc}), the animal minimises evaporative heat loss from the respiratory tract (not shown in the diagram) and the skin, and metabolic heat production is increased to offset the increased rate of the non-evaporative heat loss (conduction, convection and radiation). The rate at which the heat produced is transferred by convection in blood to the body surface is reduced, and tissue insulation is maximised, by constriction of capillary networks. The vasoconstriction occurs particularly in regions with little or no underlying muscle capable of shivering (e.g. ears, extremities of the legs), though there is intermittent reflex vasodilation in these regions to warm them and prevent freezing. External insulation is increased by piloerection.



The additional ME (E_{cold}, MJ/d) required by the animal in cold is:

$$E_{cold} = [A(T_{1c} - T_a)]/(I_t + I_e) \quad (1B.1)$$

where:

A = the surface area of its body (m^2),

I_t = tissue insulation,

I_e = external insulation.

Surface area is calculated with the following formula:

$$A = 0.09\ W^{0.66} \quad (1\ B.2)$$

A is then 0.5, 1.0, 2.0 and 3.0 m^2 at W of approximately 15, 40, 110 and 200 kg respectively, and increases by 1.0 m^2 for each further increase of about 130 kg to W = 730 kg.

Insulations are the reciprocals of conductivities. They are the temperature gradient across the tissue or coat, divided by the rate of heat loss (MJ per m^2 per day) from the surface, which

includes the evaporative loss (E, MJ/d) for I_t but not for I_e*. In the absence of heat storage (i.e. constant T_b), so that heat loss equals the metabolic heat production (MH, MJ/d):

$$I_t = A(T_b - T_s)/MH \qquad I_e = A(T_s - T_a)/(MH - E)$$

Combining these equations:

$$MH/A = [(T_b - T_a) + (E/A)\ (I_e)]/(I_t + I_e) \qquad (1B.3)$$

and by a rearrangement:

$$T_{lc} = T_b + (E/A)\ (I_e) - [(MH/A)\ (I_t + I_e)] \qquad (1\ B.4)$$

Wind reduces I_e and thus increases heat loss to the environment. This effect is described by the equation of Joyce *et al.* (1966) which, after conversion (from Mcal) to °C m^2 d/MJ, is:

$$I_e = [r/(r + F)][1/(0.481 + 0.326\ v^{0.5})] + r \ln [(r + F)/r]\ (z - 0.017v^{0.5}) \qquad (1B.5)$$

where:

r = the radius of the animal, mm;

F = hair coat or fleece depth, mm;

v = air velocity, km/h;

z = the thermal insulation/mm hair coat or fleece.

Table 1B.1. Values of the variables in equations for predicting heat loss by animals and their lower critical temperatures

			Cattle		Sheep
Variable	**Symbol**	**Units**	**Adult**	**Calf**	
1. Evaporative loss	E	MJ/m^2 d	1.5	1.5	1.3
2. Tissue insulation	I_t	°C m^2 d/MJ	1.6	0.7[A]	1.3
3. Coat insulation per mm depth	z	°C M^2 d/MJ	0.11	0.11	0.141
4. Radius	r	mm	300	130	120 (adult)
					50 (lamb)
5. Body temperature	T_b	°C	39	39	39
6. Surface area	A	m^2	0.09 kg $W^{0.66}$ (all animals)		

[A] I_t increasing from 0.64 (newborn) by 0.036/d to 1.6 (max) at 28 d old.

References:

1. Cattle: Blaxter and Wainman (1961)
   Sheep: Joyce and Blaxter (1964)

2 & 3. Adult cattle: Blaxter and Wainman (1964)
   Calf: Gonzalez-Jimenez and Blaxter (1962)
   Sheep: Joyce and Blaxter (1964); Joyce *et al.* (1966); Webster and Blaxter (1966)
   Derived by observation, from information in Brody (1945) and the references listed.

As explained on p. 27 total insulation is reduced when the hair coat or fleece is wet and the effect may be predicted from rainfall (R, mm/d) and coat depth:

$$I_{total} = I_t + [1 - 0.3(1 - \exp(-1.5\ R/F))]\ I_e \qquad (1\ B.6)$$

* In the present discussion it is necessary to distinguish only for equation 1B.5 the two components of I_e, which are the insulations provided by:
(i) the hair coat or fleece, $I_c = A(T_s - T_c) / (MH - E)$; and
(ii) the boundary layer of air at the coat surface, $I_a = A(T_c - T_a)/(MH - E)$.

The increase in radiative heat loss at T_a less than 10°C, with variation in cloud cover (C = decimal fraction of sky covered by cloud), may be allowed for by estimating operative temperature (T_0) as:

$$T_0 = (T_a - 5C) \qquad (1\ B.7)$$

Numerical values required for calculations of E_{cold} etc. are given in Table 1B.1. It will be seen that for each class of animal a single value is given for tissue insulation and for radius. Although I_t varies among individuals, as can be expected because of variation in subcutaneous fat and muscle depths, significant differences between breeds have not been established (Joyce and Blaxter 1964; Webster and Blaxter 1966). Radius will obviously vary with W and can be estimated as half the mean of four dimensions (viz. width at hips, ribs and shoulder, and chest depth), or from heart girth, but with equation 1B.5 even variation by 25% from the set radius values results in a change of only 1–2% in predicted I. Total insulations are given in Table 1.7. They include values for a 5 kg lamb and show effects of rainfall. Values for lower critical temperatures will be more immediately useful in practice than insulations because they allow rapid assessment of the likelihood of cold stress in the observed weather conditions. T_{lc} for animals with energy intakes adequate for maintenance in thermoneutral conditions are given in Table 1.8.

Appendix 1C

Main equations for predicting energy requirements

Refer to the main text for the definitions of variables in these equations.

Energy value of feeds — Equation no.

Digestibility (%)

Roughage feeds

$$OMD = 1.017\,DMD + 1.90 \quad (1.9A)$$

$$DOMD = 0.840\,DMD + 7.32 \quad (1.9B)$$

Energy and protein feeds

$$OMD = 1.00\,DMD + 3.97 \quad (1.9C)$$

$$DOMD = 0.961\,DMD + 2.11 \quad (1.9D)$$

Metabolisable energy, ME/DM, M/D (MJ/kg DM)

Roughage feeds

$$M/D = 0.172\,DMD - 1.71 \quad (1.12A)$$

$$M/D = 0.169\,OMD - 1.99 \quad (1.12B)$$

$$M/D = 0.194\,DOMD - 2.58 \quad (1.12C)$$

Silage (1.12A, B or C or either of the following)

$$M/D = 0.171\,DOMD - 1.37 \quad (1.12D)$$

$$M/D = 0.16\,DOMD \quad (1.12E)$$

Energy and protein feeds

$$M/D = 0.134\,DMD + 0.235\,EE + 1.23 \quad (1.11A)$$

$$M/D = 0.128\,OMD + 0.248\,EE + 1.06 \quad (1.11B)$$

$$M/D = 0.138\,DOMD + 0.272\,EE + 0.86 \quad (1.11C)$$

Energy requirements of animal (MJ ME/d)

Maintenance, ME_m

If production known:

$$ME_m = K.S.M(0.28W^{0.75}\exp(-0.03A))/k_m + 0.1ME_p + ME_{graze} + E_{cold} \quad (1.19)$$

If intake known:

$$ME_m = K.S.M(0.26W^{0.75}\exp(-0.03A))/k_m + 0.09MEI + ME_{graze} + E_{cold} \quad (1.20)$$

Efficiency of use of ME for maintenance, k_m

$$k_m = 0.02M/D + 0.5 \ [for\ milk\ diets, k_m = 0.85] \quad (1.21)$$

ME cost of grazing, ME_{graze} (MJ)

$$ME_{graze} = W(C.DMI(0.9 - D) + 0.0026H)/k_m \quad (1.22)$$

Energy cost in chilling weather, E_{cold} (MJ)

$$E_{cold} = A(T_{lc} - T_a)/(I_t + I_e) \quad (1.24)$$

Gestation

Weight (kg) or energy content (MJ) of foetus(es) or gravid uterus, using appropriate values of A, B and C from Table 1.9, for n young
SBW = expected birth weight/4 kg (lamb) or 40 kg (calf)

$$Y = nSBW\exp(A - B\exp(-Ct)) \quad (1.25)$$

ME required for gestation

$$ME_c = nBC\exp(-Ct)Y/0.133 \quad (1.26)$$

Weight gain (or loss)

Energy value

(a) Immature animals

Energy value of liveweight gain (MJ/kg), using appropriate values of a, b, c from Table 1.11

$$EVG = 0.92((a + cR) + (b - cR)/((1 + \exp(-6(Z - 0.4)))) \quad (1.30)$$

R = (MEI / ME_m) – 2
Z = W / SRW max. value = 1.0

(b) Mature animals

$$EVG = 0.92(13.2 + 13.8W/SRW) \quad (1.32)$$

For large lean cattle, use 9.4 instead of 13.2

Efficiency of use of ME for weight change, k_g

(a) Animals gaining weight:

For all solid diets:

$$k_g = 0.043M/D \ [for\ milk\ diets, k_g = 0.7] \quad (1.36)$$

An alternative equation for herbage diets, which allows for seasonal change:

$$k_g = 0.035M/D(1+0.33Le)(1.0+0.12(\lambda \sin(0.0172T)/40)) \quad (1.37)$$

For lactating animals:

$$k_g = 0.60$$

(b) Animals losing weight:

Efficiency of use of mobilised tissue for maintenance:

$$k_m = 0.80$$

For lactating animals; efficiency of use of tissue for milk production:

$$k_g = 0.84$$

Dietary ME (MJ) equivalent of LWC (kg) = LWC * EVG/k_g

Milk production

Energy content of milk (MJ/kg)

(a) Cows

Alternative equations, depending on which constituents (g/kg) are known:

$$E = 0.0458F + 1.222$$

$$E = 0.0386F + 0.0205SNF - 0.236 \quad (1.39)$$

$$E = 0.0381F + 0.0245P + 0.0165L \quad (1.40)$$

(b) Sheep

$$E = 0.0328F + 0.0025D + 2.203 \quad (1.41)$$

Efficiency of use of ME for milk production, k_l:

$$k_l = 0.02M/D + 0.4 \quad (1.43)$$

ME (MJ) required for milk production (kg) = E / k_l

Chapter 2

Protein

Summary

The net protein maintenance requirement of an animal is the sum of endogenous urinary protein, endogenous faecal protein and, for cattle, dermal protein loss. The total net protein requirement is converted to truly digestible protein leaving the stomach, DPLS, by assuming DPLS is used with an efficiency of 0.7 for all purposes except for wool growth where it is assumed wool protein = 0.6 DPLS.

Wool protein production is calculated from either ME intake or CP intake, whichever is limiting, and varies with the genetic potential of the sheep, adjusted for age, pregnancy and lactation.

Estimates of net protein requirements for gestation and milk production are similar to those of the ARC (1980). The protein in empty body gain is estimated with separate equations for growing animals and mature animals; variation with type of animal being allowed for by the use of an appropriate Standard Reference Weight and specific parameters for large lean cattle (see Chapter 1).

In most feeding situations, the supply of protein to meet these requirements is dominated by the yield of microbial crude protein from the microbial population flowing to the small intestine. The yield is a direct function of the intake of fermentable ME, provided that at least this amount of rumen-degraded protein is available from the effective degradation of dietary protein. The digestible fraction of the undegraded dietary protein and 0.6 of the microbial protein make up the total DPLS supply. Calculation of the CP concentration required in the diet to meet the needs of specific animals is therefore complicated by the effect of variation in the effective degradation rate of the dietary protein.

Tables are provided that illustrate the estimation of protein requirements; the examples are the same as those used in Chapter 1 to illustrate ME requirements and the prediction of liveweight gain or milk yield from given ME intakes. As with the energy requirements, an unlimited range of such estimates may be made from a spreadsheet program (CP Required) that is freely available from a website. The main equations used in making these predictions are listed in Appendix 2B.

Guidelines are given for the use of protein or non-protein supplements with poor-quality forages where the dietary supply of rumen-degraded protein, or less usually undegraded dietary protein, may limit feed intake and animal productivity.

Introduction

It is important for the intensive livestock industries to be able to specify and provide for the animals' protein requirements as precisely as possible because protein feeds are generally the most expensive components of their rations. A protein feeding system is also needed for grazing animals, to identify effective and economic procedures for supplementary feeding of, for example, lactating dairy cows. Moreover, the low protein content of tropical and subtropical pastures during the dry season, Mediterranean-type pastures during summer, and native pastures on the Tablelands during the winter, reduces the growth rates of young animals. It also extends the time to puberty and first pregnancy, and adversely affects reproductive performance and lactation in mature animals (Hennessy 1983; Lee *et al.* 1985). In these situations, livestock managers need guidance as to whether the animals would respond to a non-protein nitrogen (NPN) or a protein supplement, and, if so, of what type and in what amount. It is also necessary to distinguish between and specify the individual requirements for two types of protein supplement, viz. those containing proteins that are extensively degraded within the rumen and essentially provide NPN, and those containing proteins that are not extensively degraded but are digestible in the small intestine.

It is now understood that protein feeding systems for ruminants must take into account (*a*) the provision in the rumen of nitrogen sources and other nutrients in amounts sufficient to promote optimum rates of fermentative digestion and growth by ruminal micro-organisms; (*b*) the provision of dietary amino acids post-ruminally to augment those amino acids provided by intestinal digestion of the micro-organisms; and (*c*) interactions between the availability of amino acids to the tissues, and other nutrients that may affect the efficiency of utilisation of absorbed amino acids, and may also affect feed intake. Protein feeding systems based on a simplistic view of protein metabolism such as digestible true or crude protein do not take account of these cardinal elements in the protein nutrition of ruminants.

Approaches exemplified by the systems developed in the United Kingdom (AFRC 1992), France (Jarrige 1989), Scandinavia (NKJ 1985) and the USA (NRC 1985*b* and Fox *et al.* 2004) go some way towards achieving the above objectives. In general these systems envisage a demand for amino acids to meet the needs for essential metabolic processes in tissues and for the deposition of protein during growth, reproduction, lactation and wool growth. These needs are compared with predictions of the DPLS absorbed from the small intestine from two main sources, namely microbial protein (MCP) and ruminally-undegraded dietary protein (UDP). Prediction of the amounts of amino acids made available from these two sources is approached in a variety of ways, usually involving a number of simplifying assumptions. The use in all these systems of dietary energy as well as N supplies, variously expressed, as bases for predicting microbial protein supply gives recognition to the interdependence between energy and protein in this as well as in all other processes in nutrition.

An alternative model of ruminant digestion and metabolism, described by Black *et al.* (1982), takes account of the dynamic interactions in these processes. Information required to operate this model includes definition of a number of physical and chemical properties of the diet that govern the rates and extent of breakdown of dietary components in the rumen, their use by the micro-organisms therein, or their 'escape' from the rumen. Predictions of outputs from the rumen and of the quantities of various nutrients absorbed are then matched with a simulation of tissue metabolism to predict animal performance.

A related simulation of metabolism (Black *et al.* 1986) was adopted in the companion Report on Feeding Standards for Pigs, but a major impediment to its adoption here is the paucity of high-quality information on ruminant feeds, which would limit its general use in the widely varying nutritional environments in Australia. Most of the ruminant animals in Australia obtain most or all of their feed by grazing, even allowing for the considerable quantities of supplementary feeds given to dairy cows and for cattle and lambs in feedlots. Objective nutritional management is therefore primarily, and very heavily, dependent on predictions of the amount and quality of the pasture ingested. The method of intake prediction described by Freer *et al.* (1997, 2006) has been developed and adopted in the present Report (Chapter 6). Although realistic allowances have been made for variation in intake between animals varying in type and physiological state, and between pastures (that in Australia vary immensely in plant species, herbage availability, composition and digestibility) the predicted intakes are inevitably imprecise. There would be no less imprecision in predictions of amino acid flows to the small intestine made with a model of rumen digestion, even if the model did predict rather exactly the outcomes of digestion when a known amount of a well-characterised diet was eaten.

For such reasons the protein feeding system developed in this Report is generically similar to systems adopted elsewhere (e.g. Roy *et al.* 1977) and can be regarded as a framework for future research efforts.

Terminology

The protein values of feeds and the protein requirements of ruminants are expressed here principally in terms of crude protein (CP = total N × 6.25) and related measures. The assumption of 16% N in proteins, that is implied by the factor 6.25, or usually 6.38 (i.e. 15.67% N) for milk protein, is a generalisation that ranks the N in amides, nucleic acids, and other compounds equally with the N in amino acids. NPN accounts for about 0.2 of the N in fresh herbage, though much of it is present as free amino acids, and it may be as much as 0.75 of the N in silage; in these and a wide range of other feeds the factor for converting total N to true protein is considerably less than 6.25 (Tkachuk 1969; Boisen *et al.* 1987). This matter is of much importance in the feeding of non-ruminants because the protein value of feeds is determined by their amino acid content, but NPN has nutritional value for ruminants because it is incorporated in the microbial protein synthesised during ruminal fermentation, which is an important part of their protein supply.

In some commercial test laboratories the Dumas technique is replacing the traditional Kjeldahl procedure for routine N analysis. The Dumas procedure measures all N, including nitrate, and gives higher values for the 'protein' content of some feeds (Etheridge *et al.* 1998). The protein requirements suggested in this report are based on Kjeldahl estimates and values based on Dumas analyses should be corrected for nitrate in problem feeds, such as green fodder crops.

This report **adopts** CP = N × 6.25 (or 6.38 for milk) because it is commonly used in the practical feeding of ruminants in Australia, and overseas where it is a generally agreed convention (e.g. NRC 1985*b*; Jarrige and Alderman 1987). The feed trade in a number of countries, including Australia, is obliged by law to use 6.25 to calculate and state CP. Consistent use of this convention in the discussion that follows will avoid the confusion that could arise if free use were made of both N and N × 6.25 as units of measurement.

Digestion

Proteolytic enzymes in ingested plant cells (Theodorou *et al.* 1996) and from the microbial population in the rumen (Attwood and Reilly 1996) degrade some of the total crude protein intake giving rise to ruminally-degraded protein (RDP); the remaining fraction is undegraded dietary protein (UDP), i.e. UDP = CP – RDP. Micro-organisms assimilate the RDP for the synthesis, during their growth, of protein and other nitrogenous constituents. As shown in Fig. 2.1, an additional source of N for the micro-organisms is endogenous material entering the rumen in forms that include proteins in saliva, sloughed epithelial cells and urea transferred from blood to saliva and across the rumen wall. Much of the RDP and of the endogenous material is degraded to ammonia that is used extensively by the micro-organisms, though some species use and may even require N in the form of peptides or amino acids. All species also require various mineral nutrients, including sulfur that is essential for protein synthesis, and cobalt for which the only known function in ruminants is in the microbial synthesis of vitamin B_{12} (see Chapter 4). In addition, of course, the micro-organisms must have a supply of fermentable energy for their maintenance and synthesis of numerous polymers during growth. The major supply of energy, quantitatively, comes from the fermentation of the carbohydrates in the animal's feed but protein and other digestible polymers also contribute energy when fermented. The major by-products of the fermentation, in addition to heat and methane (Chapter 1), are the short-chain fatty acids (SCFA) acetic, propionic and butyric, which in sum provide ruminants with around two-thirds of the total amount of ME they gain from their diets. Smaller amounts of higher SCFA (C_4, C_5) are formed and also branched-chain fatty acids that come mainly from the fermentation of amino acids (el-Shazley 1952). The microbial cells are a major source of amino acids but are also a significant source of ME for the host animal.

The key to an understanding of factors controlling microbial protein synthesis in the rumen was provided by the observations of Bauchop and Elsden (1960) of a reasonable constancy in the yield of cells of several types of anaerobic bacteria when expressed in relation to the amount of adenosine triphosphate (ATP) theoretically made available from the fermentation of substrate. Walker (1965) presented calculations of the quantities of ATP provided from ruminal fermentation of roughages, and related ATP yields to the quantities of individual SCFA produced. This approach, which also showed that microbial cell yield and the microbial crude protein (MCP) that entered the small intestine could be calculated from a knowledge of ATP production, was confirmed by Hogan and Weston (1970) in quantitative studies on the digestion of dried grasses and clovers by sheep. In that work, the production of SCFA and of a component of bacterial cells, diaminopimelic acid, were shown to be related to the amounts of organic matter apparently digested in the rumen (OMADR) and in the whole digestive tract (DOM). With 23 grasses and clovers varying in OM digestibility from 0.56–0.81, the production of SCFA was equivalent to 8.3–8.7 mole/kg DOM, confirming the value of the readily measurable DOM as an index of potential energy supply to the microbes and of MCP yield.

Energy supply for microbial synthesis is more usefully expressed in terms of FOM, the amount of feed OM that has been fermented in the rumen or, preferably, FME, the fermentable ME of a diet. These terms exclude the DOM or ME, respectively, represented by the amounts of ether-extractable components and undegraded protein in the diet and the organic acids present in silage. MCP yields will here be expressed directly as g/kg FOM or g/MJ of FME.

For efficient capture of the N from RDP in microbial CP the supply of energy as ATP (and necessary nutrients) should be quantitatively sufficient, and should also be supplied at rates at

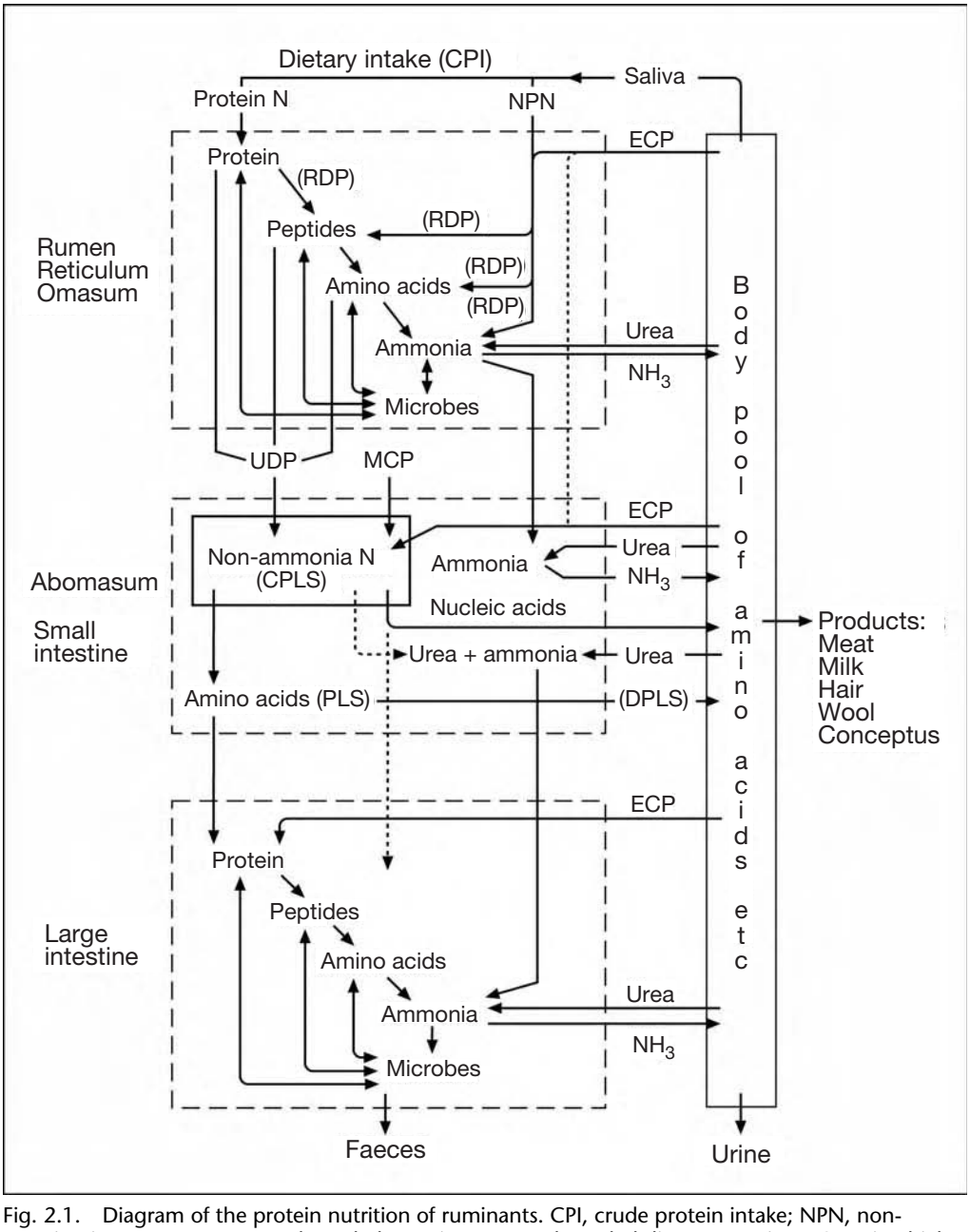


Fig. 2.1. Diagram of the protein nutrition of ruminants. CPI, crude protein intake; NPN, non-protein nitrogen; RDP, rumen-degraded protein; UDP, undegraded dietary protein; MCP, microbial crude protein; CPLS, crude protein leaving stomach (UDP + MCP); PLS, true protein leaving stomach = CPLS minus (nucleic acid N × 6.25); DPLS, digestible true protein leaving stomach; ECP, endogenous crude protein.

least commensurate with the rates at which N substrates become available for microbial assimilation. This thinking has led to the argument that the rates of supply of FME and RDP need to be 'synchronous' (Sinclair *et al.* 1993) and that the 'avoidance of asynchronous patterns of nutrient release within the rumen can improve energy efficiency' (Richardson *et al.* 2003: 1332). These

workers found that efficiency of RDP capture was increased and growth of lambs was improved with synchrony of nutrient supply to the rumen. Similarly, Kim *et al.* (1999) have shown the benefits for MCP synthesis in dairy cattle of synchronising the availability of FME (maltodextrin) with the nitrogenous release from a silage/barley/groundnut meal diet (196 g CP/kg DM) and Trevaskis *et al.* (2001) carried out a series of experiments with sheep that indicated higher efficiencies of nutrient use were associated with synchronising energy and protein supplies for rumen micro-organisms.

On the other hand, other workers have pointed out that asynchronous rates of supply of FME and RDP from the diet can be ameliorated by recycling of endogenous CP and have used this suggestion to explain why beneficial responses in microbial protein synthesis or growth were not apparent when dietary energy and protein supplies were synchronised experimentally (Kim *et al.* 1993; Valkeners *et al.* 2006).

Transient excesses of ammonia relative to energy supply, whether from intermittent intake of urea or rapid degradation of the protein in high-protein feed such as young green pasture, will be absorbed from the rumen and converted to urea in the liver. If much of this urea is excreted in the urine, efficiencies of RDP capture in MCP will be low and output of CP from the rumen will be less than the input. Conversely, as shown in Fig. 2.1, when the animal eats feed with low CP there can be a net gain of N in the rumen by recycling of urea, with the result that more N leaves the stomach through the pylorus than enters in the feed (Clarke *et al.* 1966).

The total N in digesta minus the N present as ammonia is termed non-ammonia nitrogen (NAN). The crude protein leaving the stomach (CPLS) is (NAN × 6.25) and has three components where usually, MCP > UDP > endogenous crude protein (ECP). Thus:

$$\text{CPLS} = b_1\text{FOM} + b_2\text{CPI} + \text{ECP} \tag{2.1}$$

where b_1 is the MCP yield g/kg FOM (alternatively the MCP synthesised per MJ of FME), and b_2 is the fraction of the CPI that has not been degraded during passage through the rumen (i.e. UDP, which equals CPI minus RDP). The contribution to CPLS of the relatively small amount of ECP is usually disregarded in protein feeding systems; the subsequent absorption of amino acids from this material does not give rise to a net gain of amino acids for the tissues. Allowance should be made for ECP when measurements of the degradation of the CPI are made *in vivo* (see p. 79).

About 15% of the N in MCP is present in the form of nucleic acids and other non-amino acid N compounds (Russell *et al.* 1992). Consequently the protein leaving the stomach (PLS), ignoring ECP, is:

$$\text{PLS} = 0.85\ (b_1\text{FOM}) + \text{UDP} \tag{2.2}$$

With forage diets, the amino acid composition of PLS is rather uniform (Lindsay and Armstrong 1982). This is because there is little variation in the composition of the major contributor, microbial protein (Table 4.14 of Ørskov 1982), which is also rather similar to the amino acid composition of forage proteins. There is considerable variation in the composition of the free amino acids in forages but this usually has little effect on the composition of PLS owing to their degradation in the rumen. The presence of condensed tannins reduces protein degradation (Barry and Manley 1984) and increases the quantities of essential amino acids absorbed (Waghorn *et al.* 1987). The quantity of UDP can also be increased if feeds are protected from microbial attack by physical (e.g. heat) or chemical (e.g. formaldehyde) treatment.

The truly digestible protein leaving the stomach (DPLS) is:

$$\text{DPLS} = a_1\ (0.85\ b_1\ \text{FOM}) + a_2(\text{UDP}) \qquad (2.3)$$

where a_1 and a_2 are digestibilities in the small intestine (duodenum, jejunum, ileum) of the two components of PLS.

Further fermentation occurs in the caecum and colon, yielding 0.08–0.17 of total SCFA production in the alimentary tract, equivalent to 0.09–0.20 of the quantity of SCFA produced in the rumen (Ulyatt *et al.* 1975; Armstrong 1982). MCP is synthesised but it is thought that no peptides or amino acids are absorbed by the animal from this part of the tract.

Requirements

In general, the metabolism of protein in the tissues of ruminant animals is similar to that in other mammals. They require the 10 amino acids that are classed as 'essential' because synthesis in mammalian tissues is nil or very small in extent, and they must gain these directly from their feed or from MCP. Amino acids are used mainly for synthesis of proteins, which are the major compounds in muscles, connective tissues, the digestive tract and other organs in the body, the skin, pelage, hooves, horns and wool. Many of the proteins function as enzymes to catalyse biochemical reactions; as hormones to regulate the rates of synthesis and degradation of various materials; as antibodies to confer immunity to invasive organisms or in a variety of other specialised functions such as muscle contraction and fibrin for blood clotting. Amino acids that are present in excess of requirements for protein synthesis are deaminated and the resulting keto-acids may be oxidised or may contribute to gluceogenesis. The amino group is carried to the liver where it is incorporated into urea.

Proteins are continuously synthesised and catabolised in body tissues. This turnover process is important to overall regulation of protein synthesis and hence to the adaptability of the animal to changing physiological needs (see Oddy and Sainz 2002). Turnover occurs both intra- and extra-cellularly. The magnitude and significance of the latter process is often not fully appreciated; endogenous proteins entering into the digestive tract in secretions and sloughed cells are effectively part of endogenous turnover because they must be degraded to peptides and amino acids before they can be re-absorbed and again synthesised into protein (Nolan 1983). The presence of internal parasites can increase the magnitude of this tissue–gut turnover (Rowe *et al.* 1988).

If protein synthesis and degradation rates are equal there is a dynamic equilibrium. If not, there is a net deposition or net loss, but these net rates are much less than the rates of synthesis and degradation. For example, in a study with lambs of 20 kg live weight, Davis *et al.* (1981) estimated that about 600 g protein/d was synthesised while only 20–30 g/d was deposited in the body, equivalent to a liveweight gain of around 190 g/d. In cattle, dietary amino acid supply and protein gain represent only approximately 0.31 and 0.06, respectively, of protein synthesis and degradation in animals consuming more than maintenance energy (Lobley *et al.* 1987). High rates of protein turnover use a significant amount of maintenance energy and Oddy and Sainz (2002) have suggested that changes in protein accretion:protein synthesis (that can vary with genotype, age and rate of gain) should be considered when making predictions of efficiency of energy retention in gain in models of energy requirements in ruminants.

During protein catabolism in tissues, the essential amino acids released are efficiently re-used in protein synthesis, but some that enter the plasma pool are still oxidised to an extent (5–19%; Mathers and Miller 1979; Cronjé 1987) that is probably dependent on whether the supplies of

particular amino acids are greater or less than immediate requirements. Because there is little capacity for storage of amino acids, those in excess of immediate requirements are deaminated and their carbon moieties are oxidised. Some essential amino acids are also modified during metabolism to components that are not re-utilised (e.g. the methylated forms of histidine and lysine) and some are lost in wool, hair, suint, scurf, hooves and horns. Protein turnover therefore results in obligatory losses of amino acids that can only be replaced by the uptake of dietary or microbial amino acids from the alimentary tract. DPLS is necessary to replace these losses and to enable the animal to maintain its current body condition.

The net requirements for protein, as for energy, are assessed factorially. They are then expressed as the required dietary equivalent as DPLS by applying a value, or values, for the efficiency of use of the DPLS by the tissues. This is analogous to the procedures described by equations 1.3 and 1.4. The net protein requirements can similarly be perceived as the minimum amount needed to maintain tissue protein mass plus the quantities of protein deposited in growth, wool production, or during gestation, and secreted in milk.

As with energy, it can be expected that the 'maintenance' protein requirement would increase with increasing feed intake (level of production), particularly because of an increase in EFP excretion. As discussed later, this change in EFP could affect the magnitude of a second inevitable N loss: the endogenous excretion in urine (EUP). The third inevitable loss is through sweat, scurf, hair, wool, hooves and horns. Determination of the net protein requirements for growth is dependent on prediction of the quantity of protein in body gain. Similarly, the net requirement during gestation is the rate of accumulation of protein in the conceptus. For milk production, and wool, it is the quantity of protein exported in these products. In all instances the important, but difficult, objective is to predict the responses of animals to changes in supplies of DPLS, taking account of the interactions with the supplies and metabolism of energy and other nutrients.

The protein value of feeds

As explained above, the primary measures of the protein values of feeds for ruminants are: (*a*) the extent to which their proteins will be degraded in the rumen, indicating the contribution of UDP to CPLS, and (*b*) the MCP yield from the RDP, which is assessed by reference to the quantity of dietary energy available to the micro-organisms (equations 2.1 and 2.2).

Degradation in the rumen

Effective degradation (Edg) indicates the protein degradability, dg, which will occur at a specified rumen outflow rate and is described by the expression:

$$\text{Edg} = 1 - (\text{dietary protein leaving stomach/CPI}) \quad (2.4)$$

Estimates have been made from both *in vivo* and *in vitro* studies.

Measurement in vivo

Measurement *in vivo* requires the determination of total CPLS, the fraction that is microbial in origin, and an estimate of the endogenous component (ECP). Thus:

$$\text{Edg} = 1 - [(\text{CPLS} - \text{MCP} - \text{ECP})/\text{CPI}] \quad (2.5)$$

Reliable measurement of CPLS and MCP requires considerable skills, but even with these the results are not exact and Miller (1982) suggests that about 10 animals are needed if degradation is to be determined with the precision required for its use in practical diet formulation. Most determinations have been made with sheep because the use of cattle presents greater technical problems.

The evaluation of ECP is problematical because of the paucity of information. Hart *et al.* (1982) found that the flow of ECP to the omasum of cattle given a protein-free diet was 12.5 g/kg DMI and that a further 22.8 g/kg DMI was added in the abomasum. Harrop (1974) reported endogenous protein inputs into the abomasum of sheep in the range of 12–17.3 g/d.

In a number of reports of *in vivo* measurements, and those used by the ARC (1980, 1984), the contribution of ECP has been ignored. This can have a considerable effect on the result obtained. For example, in nine experiments with sheep grazing temperate pastures (Corbett and Pickering 1983) the mean CPI was 190 g/d and CPLS was 140.5 g/d of which, on average, 0.73 was microbial. When the ECP contribution in the sheep, average live weight 35 kg, was assumed to be 12.5 g/d the mean value for the fraction of dietary CP degraded was 0.87 and for the flow of UDP was about 25 g/d. When ECP was assumed to be 6.25 g/d or nil, the values for degradation were respectively 0.83 and 0.79 and for the UDP were about 32.5 and 40 g/d. The Grassland Research Institute (1982) reported that the minimum value for the degradation of the protein in fresh forage was 0.72, but with an allowance for ECP it was 0.88–0.99. Still larger effects on dg values can occur from ignoring ECP when CPI and CPLS are low.

Measurement in vitro

It is desirable to establish a laboratory test of degradability (dg) as an alternative to animal trials, analogous to the *in vitro* technique for determining feed digestibility. Broderick (1994) has reviewed a number of procedures, including incubations with ruminal fluid or enzymes, and solubilities in water alone, buffer solutions, and other solvents.

The most common technique for estimating dg is the so-called *in sacco* procedure that involves placing samples of feed in porous polyester or nylon bags that are suspended within the rumen of fistulated animals, and observing the rates of disappearance of DM, N and other components. It is important that evaluation of degradability *in sacco* should be by a standardised method. AFRC (1992) concluded that the variability between laboratories in published estimates up to that date was unacceptably high and proposed that the procedure set out in Appendix 2A of this Report should be strictly adhered to (see also Vanzant *et al.* 1998). The technique may be applied to chopped fresh forages or extrusa samples from fistulated animals, either in the fresh state (Dove and McCormack 1986) or after freeze-drying (Wales *et al.* 1999). However, as discussed below, the degradability of medium- to low-quality forages will be underestimated unless allowance is made for microbial contamination of the sample during incubation (see notes to Appendix 2A).

Effective degradation (Edg)

The actual extent of CP degradation with any given feed in practical feeding will differ from the degradability value estimated *in vitro*, particularly because of variation in the feed's mean residence time (MRT, h) in the rumen and hence its fractional outflow rate per h (k = 1/MRT). As MRT decreases with increasing intake of the feed, k increases and Edg decreases. There is also

variation in Edg with the physical state of the feed (e.g. ground *v.* long forage; Faichney 1983; Elimam and Ørskov 1984), with the types of other feeds, if any, in the diet, and with the physiological state of the animal. For example, k increases during pregnancy and lactation (Weston 1979; Weston *et al.* 1983) and as ambient temperature falls (Kennedy *et al.* 1986). In addition, Weston and Margan (1979) reported an increase in UDP flow with age in lambs as they grew from 18 kg at 15 weeks to 44 kg at 40 weeks.

Ørskov and McDonald (1979) showed that dg of a feed sample incubated *in sacco* over time t (h) can be described by the equation:

$$\text{dg} = a + b\,(1 - \exp(-c\text{t})) \tag{2.6}$$

where:

a = the soluble component of the CP, which disappears rapidly;

$a + b$ = the total amount of potentially degradable CP in the feed; and

c = the rate of disappearance, per h, of the CP in component b.

The Edg of the feed varies with the fractional outflow rate, k (/h) and can be calculated as:

$$\text{Edg} = a + b\,c/(c + k) \tag{2.7}$$

The fraction of protein escaping undegraded (Udg = 1 – Edg) is given by the complementary equation:

$$\text{Udg} = b\,k/(c+k) + d \tag{2.8}$$

where d is the fraction of protein that is completely indigestible.

There is some difficulty in establishing what value of k should be used to predict effective degradability in practice. The Feed Evaluation Unit of the UK Agricultural Development and Advisory Service has now published values, from *in sacco* measurements, of dg at three values of k for a variety of feeds (ADAS 1989, MAFF 1990). It proposes the following applications:

$k = 0.02$: cattle and sheep given completely ground diets or a very low level of feeding of a mixed diet, equivalent to maintenance.

$k = 0.05$: calves, low-yielding dairy cows, beef cattle and sheep given a high level of mixed diets.

$k = 0.08$: high-yielding dairy cows (fed at more than twice maintenance) given mixed diets.

A further problem with the *in sacco* technique is that disappearance of N from the bag is equated with degradation, but the measured disappearance may be greater or less than the true value for degradation. The feed residues in the bag, even after thorough washing, will contain microbial N. Mathers and Aitchison (1981) concluded from studies on lucerne that microbial contamination would lead to significant underestimation of degradability for feeds with a low, but potentially highly degradable, protein content, but would be unimportant for feeds with high CP especially if it was of low degradability. Varvikko and Lindberg (1985) similarly concluded that microbial contamination would have rather little effect on observed degradability values for high CP feeds (e.g. rapeseed meal), and stated that markedly false results are probable with starchy feeds (e.g. barley) and with forages, particularly those with low CP.

Rodriguez and Gonzalez (2006) determined the effective degradability of 14 feeds: barley and maize grains, soyabean and sunflower meals, full-fat soyabean, maize gluten feed, soyabean hulls, brewers dried grains, sugarbeet pulp, wheat bran, lucerne and vetch-oat hays and barley and lentil straws. They infused ^{15}N-ammonium sulfate to label the rumen bacteria and determined the microbial contamination (CP/100 mg CP). Uncorrected results underestimated the effective degradability of both DM and CP by 0.6% to 13% for feeds other than barley straw, for

which the error was even higher. Excluding maize grain, the microbial contamination of CP was positively related to the cellulose content of the feeds and negatively related to their CP content and apparent effective degradability ($R^2 = 0.87$).

To overcome the problem of microbial contamination of forage samples during incubation, without the difficulties associated with the correction for microbial protein (Broderick 1994), the *in sacco* procedure has been used to estimate directly the UDP in forages (using equation 2.8) and hence the RDP (Mass *et al.* 1999, Klopfenstein *et al.* 2001). This technique is based on the assumption that the neutral detergent insoluble protein (NDIP) in the forage represents the primary UDP fraction in feedstuffs (Sniffen *et al.* 1992). The NDIP, less the ADIP, is potentially degradable and, as proposed by Broderick (1994), the rate constant *c* for the disappearance of this fraction from the incubation bag is estimated and UDP calculated from equation 2.9, using the same outflow rate, *k*, as before.

$$UDP = ADIP + (NDIP - ADIP)\left(\frac{k}{k+c}\right) \tag{2.9}$$

Tests made by Mass *et al.* (1999) on eight forages ranging in *in vitro* DMD (IVDMD%) from 49–74% showed that Edg estimated using this approach (equation 2.9, for $k = 0.02$) was significantly higher than from the standard technique that did not include a correction for microbial contamination. It can be calculated from their results that the effect on Edg was inversely related to IVDMD; the error almost disappeared at an IVDMD of about 75% but, at 49%, the procedure that ignored microbial contamination underestimated Edg by 0.26. The magnitude of this error throws considerable doubt on most of the published values for protein degradation in poor- to moderate-quality forages.

Another difficulty is that some material may have disappeared from the bag without being completely degraded. This will include some small particles that have escaped and that might be only partially degradable, though these would generally amount to a rather small fraction of the sample mass. More particularly, the disappearance of some proteins may be by solution rather more than by degradation; this has been demonstrated for the albumens present in feeds such as peas (Spencer *et al.* 1988). For this reason, in this Report we do not follow the proposal by Webster (1987) to distinguish fraction *a* (equation 2.6) as 'quickly degraded protein' (i.e. QDP), likely to be converted to MCP with an efficiency of less than 1.0, in contrast to the more 'slowly degraded protein' fraction *b* (i.e. SDP = RDP – QDP).

Prediction from feed composition

One practical alternative to the use of an artificial fibre bag for predicting degradability of the N-component of feedstuffs is to use a relationship between degradability and characteristics of the plant material that are easily determined by chemical analyses. Webster *et al.* (1988) reported the following relationship for grass hays and silages, ranging in Edg from 0.8 to 0.2, based on CP and neutral detergent fibre, NDF, concentrations (g/kg DM).

$$\text{Edg} = (0.9 - 2.4\,k)\,(\text{CP} - 0.059\,\text{NDF})/\text{CP} \tag{2.10}$$

A corresponding relationship for herbage from perennial pastures in Victoria was calculated (equation 2.11) from estimates of Edg made on 30 samples ranging in IVDMD from 84% to 58% (Wales *et al.* 1999), using the procedure set out in Appendix 2A, with minor modifications. Alternatively, Edg could be predicted from IVDMD, using equation 2.12.

$$\text{Edg} = 0.96 - 2.49\,k - 0.041\,\text{NDF/CP} \pm 0.077\ \text{(s.e.)} \tag{2.11}$$

$$\text{Edg} = 0.218 - 2.49\,k + 0.0082\ \text{IVDMD} \pm 0.081\ \text{(s.e.)} \quad (2.12)$$

As no allowance was made for microbial contamination in these estimates, it must be assumed that equations 2.10 to 2.12 will underestimate Edg of forage samples to an extent that varies with forage quality. They should not be used on samples with IVDMD of less than 70% unless a correction for microbial contamination is included. The calculated relationship from the data of Mass *et al.* (1999) at k = 0.02 includes this correction (equation 2.13).

$$\text{Edg} = 0.1852 + 0.01\ \text{IVDMD} \pm 0.08\ \text{(s.e.)} \quad (2.13)$$

Recent estimates from a range of tropical pasture species (Bowen 2003; S. McLennan pers. comm.) using the NDIP procedure (as set out in equation 2.9) on oesophageal extrusa samples are probably the most reliable values currently available for any Australian pastures. Equation 2.14 predicts much higher Edg (for $k = 0.02$) at low IVDMD (%) than would be predicted from equations 2.11 to 2.12.

$$\text{Edg} = 0.408 + 0.0072\ \text{IVDMD} \pm 0.029\ \text{(s.e.)} \quad (2.14)$$

Degradability values

This section summarises available Australian values for the degradability of the protein in protein meals and forages. It will be understood from the preceding discussion that while the values for forages indicate how the various feeds may be ranked, the actual degradations in practical feeding could be considerably different.

Table 2.1. Estimates of effective degradability of protein *in sacco* at three fractional outflow rates per h from the rumen (k), in several UK and Australian feeds

	k		
	0.02	**0.05**	**0.08**
Protein meals			
Cottonseed meal[A]	0.71	0.51	0.46
Maize gluten feed[B]	0.90	0.84	0.80
Palm kernel meal[B]	0.71	0.52	0.43
Rapeseed meal[B]	0.86	0.78	0.72
Rapeseed meal[C]	0.81	0.70	0.62
Sunflower seed meal[B]	0.88	0.80	0.74
Sunflower seed meal[C]	0.88	0.77	0.69
Soyabean meal[A]	0.76	0.57	0.46
Legume grains			
Lupins: fine meal[C]	0.95	0.93	0.92
medium meal[C]	0.85	0.72	0.64
coarse meal[C]	0.75	0.54	0.42
Cereal grains			
Barley[B]	0.90	0.85	0.81
Triticale[B]	0.93	0.90	0.87
Wheat[B]	0.93	0.90	0.87

[A] Hennessy *et al.* (1983).
[B] MAFF (1990).
[C] Freer and Dove (1984).

(a) Concentrate feeds. Some published values for the effective degradability of several feeds of UK and Australian origin are shown in Table 2.1 for three standard values of *k*. It is evident that Edg for a protein meal can vary according to its source, a major reason probably being variation in the extent of heating and in other conditions during manufacture.

Legume grains such as peas, beans or lupins are often fed coarsely ground or whole and the large particle size may significantly reduce the rate of degradation of the protein (Freer and Dove 1984), an effect that may be complicated by large differences between animals in the rate at which the ingested particles are reduced in size by chewing.

(*b*) *Fresh and dried forages.* The problems with *in sacco* estimates of protein degradability in forage samples have been discussed above. However, there are problems also with *in vivo* measurements and there is not, at present, a substantial body of data for dg, estimated at known *k* values, to compare with *in sacco* measurements. The general conclusion from the work of Mass *et al.* (1999) and Bowen (2003) is that Edg (at $k = 0.02$) in highly digestible forage is about 0.9 or greater. However, even when IVDMD has fallen to 50% Edg is at least 0.6 (temperate herbage) or 0.75 (tropical herbage); values that are much higher than would have been predicted from earlier equations.

None of the current equations will be applicable to forages containing substantial amounts of condensed tannins (CT), which are present in some legumes (e.g. *Lotus* spp., *Desmodium intortum*) though generally not in grasses. The CT protect the plant protein from ruminal degradation, to a varying extent, but not from digestion in the lower pH of the intestine (Jones and Mangan 1977; Barry and Manley 1984). The addition of formic acid during ensiling may markedly reduce dg, typically from 0.8 to 0.4 (Thomas 1982).

Microbial protein yield in the rumen

RDP requirement

The RDP fraction of feed CP consists mainly of peptides, amino acids and ammonia, all of which are assimilated by rumen micro-organisms and used for their CP synthesis. The work of Virtanen (1966) showed that dairy cattle given protein-free diets maintained an effective rumen population with access only to the ammonia arising from degradation of urea included in their protein-free diet and Allison (1969) demonstrated that most rumen bacteria can use ammonia as a N source. Nevertheless, studies in sheep fed hay diets and infused with ^{15}N-labelled ammonia sources showed that up to half of the N in rumen bacteria was derived from sources other than ammonia (Mathison and Milligan 1971). In similar experiments, Marsden *et al.* (1988) showed that about half of the leucine in bacterial protein was derived from free leucine in rumen fluid. It seems that rumen microbes use peptides or amino acids when these are available and, especially when fermentation rate is rapid, may grow faster and hence more efficiently (for more discussion, see Demeyer and Fievez 2004).

We have chosen not to consider the components of RDP separately but note that these components are considered separately in some models of N kinetics in the rumen (e.g. the Cornell model). In our scheme, however, the recognition of effects on rates of fermentation of spring *v.* autumn forage may implicitedly make some allowance for effects on efficiency of MCP synthesis (see below).

When no allowance is made for endogenous N entries into the rumen, the requirement for RDP of the micro-organisms will equal the net rate of synthesis of MCP if N substrates from the

RDP are captured with an efficiency of 1.0. There are some differences between current protein feeding systems in their assumptions about the efficiency of N capture, The assumptions made by the ARC (1984) and adopted by AFRC (1993) are: (*a*) an efficiency of 1.0 for the conversion of amino acid and peptide N into microbial N and (*b*) an apparent efficiency of 0.8 for the incorporation of N from urea or other degradable NPN sources. It was suggested that the latter value might be higher for frequent feeding of the NPN but lower if the energy source were mainly from cellulose rather than starch. The efficiency is likely to be much lower if the NPN is provided as a supplement to grazed forages.

In the above discussion it is assumed that, in addition to sufficiency of fermentable energy, there are adequate supplies of nutrients essential for microbial growth (e.g. S). Contributions of endogenous N are not readily assessed (see p. 97). They may be regarded as a buffer in the system, offsetting some deficit of RDP if, for example, the efficiency of capture of N of dietary origin were less than supposed.

Microbial yields

Published results on microbial yield are variously expressed in terms of DOMI, OMADR, FOM or FME; either of the last two is to be preferred, as each excludes dietary components (lipid, undegraded protein, acids from silage fermentation) that are not available to the micro-organisms as energy sources. The AFRC (1993) suggests that if the amounts of acids from silage fermentation are not known, an average value of 0.1 of the ME should be applied for grass silage. The AFRC (1992) analysed UK and other published data and concluded that plane of nutrition must be considered in predicting the yield of MCP per MJ FME. Their preferred values for MCP/FME were 9 g/MJ at maintenance, 10 g/MJ for growing cattle and sheep and 11 g/MJ for lactating cattle and sheep, being the values predicted at k values of 0.02, 0.05 and 0.08/h, respectively. Their general equation is a function of L, the level of feeding expressed as a multiple of ME required for maintenance. This equation is **adopted** here for supplementary feeds:

$$\text{MCP/FME (g/MJ)} = 7 + 6(1 - e^{-0.35\,L}) \qquad (2.15)$$

The stoichiometry of ruminal fermentation indicates that the maximum yield of microbial OM is unlikely to differ greatly from 360 g/kg OM actually fermented (FOM). With the assumptions that this is a maximum yield of 225 g MCP/kg FOM (i.e. 62.5% CP in the microbial OM) and that there is a flow of 30 g endogenous OM to the duodenum associated with an intake of 1 kg feed OM (J. V. Nolan pers. comm.) it can be calculated (Corbett 1987) that MCP yields in practice are unlikely to exceed 180 g MCP/kg FOM, and an efficiency of use of fermented substrates by the micro-organisms that is about 0.8 of the theoretical maximum. The ARC (1984) value of 200 g MCP/kg OMADR (= 130 g MCP/kg DOM = 8.25 g MCP/MJ of ME) represents a microbial efficiency of about 0.65.

It has generally been found that the lowest MCP yields among feed classes are from silages. For example, a review by Thomas (1982) of 12 studies with sheep given silages made from unwilted or wilted grass, without additions or with formic acid and/or formaldehyde, showed a mean MCP yield of 93 g MCP/kg DOMI, for a low microbial efficiency of *c.* 0.35.

Table 2.2 shows that MCP yields with fresh forage diets from temperate pastures can, as stated by the ARC (1984), be considerably higher than their assumed 200 g/kg OMADR (e.g. Walker *et al.* 1975), but this is not consistently so. In the 12 experiments of Corbett and Pickering (1983, and unpublished data) with sheep grazing a variety of spring growths, the mean MCP

yield was 279 g/kg OMADR, or 182 g/kg DOMI (s.d. ± 11 g). With later growths of the same pastures, the mean MCP yield in eight experiments was 199 g/kg OMADR, or 144 g/kg DOMI (s.d. ± 14 g) that is about 0.8 of the spring value. Van Vuuren *et al.* (1992) reported a decrease in microbial N flow between summer and autumn, from 22.9 to 16.7 g/kg OM apparently digested in the rumen, in cows offered fresh ryegrass of the same OM digestibility.

Table 2.2. Estimates of microbial crude protein (MCP) yields from temperate forages in the rumen of sheep (sulfur-35 marker) and cattle (nitrogen-15 marker) in relation to the organic matter apparently digested in the rumen (OMADR) and to the digestible organic matter intake (DOMI)

Forage (and number of experiments)	Season or stage of growth	MCP			Reference
		Mean OMD[A]	OMADR g/kg	DOMI g/kg	
Grazed pastures					
Various[B] (12)	Early (spring)	0.73	279	182	1
Various[B] (8)	Later	0.74	199	144	1
Perennial ryegrass	Spring	0.82	255	191	2
Perennial ryegrass	Autumn	0.82	117	99	2
Cut forages: *sheep*					
Sub. clover (1)	Pre-wilting	0.81	193	159	3
Sub. clover (2)	Wilting/wilted	0.62	212	123	3
Sub. clover (1)	Mature	0.65	178	124	3
Cut forages: cattle					
Perennial ryegrass (1)	Early (spring)	0.83	356	215	4[C]
Perennial ryegrass (1)	Mid (summer)	0.82	316	212	4
Perennial ryegrass (1)	Late (late summer)	0.81	294	186	4
White clover (1)	Early (spring)	0.83	309	196	4
White clover (1)	Mid (summer)	0.77	522	236	4
White clover (1)	Late (late summer)	0.81	312	185	4

[A] Organic matter digestibility.

[B] See text.

[C] All four-week-old regrowths after harvest and N fertiliser.

References: 1. Corbett and Pickering (1983; unpublished data).
2. Dove and Milne (1994).
3. Hume and Purser (1975).
4. Beever *et al.* (1986).

A wide range of data from experiments with tropical (C4) grasses, reviewed by Bowen (2003), shows much lower efficiency of MCP production (30–140 g MCP/kg DOMI). To a large extent this can be attributed to low levels of RDP but Bowen concludes that tropical species have a lower plateau of efficiency even when RDP supply is non-limiting. In steers grazing a range of tropical pasture species, MCP yield did not reach 130 g/kg DOMI until the supply of RDP was 200 g/kg DOMI.

Table 2.3. Estimated yields of microbial crude protein (MCP) from temperate pastures in spring and autumn and from supplementary feeds, expressed as g per MJ of FME, and contributions of the MCP to protein leaving the stomach (PLS) and digestible protein leaving the stomach (DPLS) at a maintenance level of feeding (L = 1) and at twice this level (L = 2)

	Spring herbage	Autumn herbage	Supplements
L = 1			
MCP	9.4	8.7	9.4
PLS	8.0	7.4	8.0
DPLS	5.6	5.2	5.6
L = 2			
MCP	11.1	10.4	10.3
PLS	9.4	8.8	8.8
DPLS	6.7	6.2	6.2

It appears probable that a seasonal change in the MCP yield from temperate forage diets is associated with the changes in their chemical composition. As suggested in Chapter 1 (see p. 42), a change in the fermentation end-products also results in lower NE values for the animal from autumn compared with spring growths of temperate pastures. In particular, the decrease in the water-soluble carbohydrate (WSC) content in successive growths represents a decrease in a readily available supply of energy for the micro-organisms, which, as a result, are less efficient in capturing N. The higher WSC content of spring pasture is associated with the production of ruminal SCFA having an acetate to propionate ratio of less than three, compared with ratios between three and four for autumn pasture (Beever *et al.* 1978; Corbett 1987; Dove and Milne 1994).

It is concluded that, provided there is no inadequacy of N or other nutrients (e.g. S) for the microbes, and in the absence of modifiers of rumen fermentation (see Chapter 7), the MCP contribution to CPLS (coefficient b_1 in equation 2.1) for supplementary feeds should be assessed with equation 2.15. For fresh temperate forages, the **adopted** function (equation 2.16) has been modified to account for seasonal changes in MCP yield (g/MJ); an equation of a similar form to equation 1.38 for predicting k_g in herbage diets. Some examples are shown in Table 2.3.

$$MCP = FME(7 + 5(1 - e^{-0.35L}))(1.0 + 0.1(\lambda \sin(0.0172T)/40)) \quad (2.16)$$

where λ is the latitude (negative in the southern hemisphere);
and T is the day of the year from 1 January.

For forages from tropical pastures, the efficiency of synthesis will be lower and it is to be expected that seasonal (i.e. spring *v.* autumn) differences will be of less importance. In the absence of better information, the function **adopted** at present (equation 2.17) predicts MCP yield from a modified form of equation 2.15.

$$MCP / FME = 6 + 6(1 - e^{-0.35L}) \quad (2.17)$$

In forages providing inadequate RDP (or S) to meet the predicted yield, the estimate should be reduced in proportion, e.g. if the intake of RDP is only 0.7 of that theoretically required for MCP synthesis, then the yield will be only 0.7 of this value.

Digestible protein leaving the stomach (DPLS)

The protein value of feeds has finally to be expressed as DPLS (see equation 2.3), the same units as those used to describe the dietary protein needs of the animal. Of the MCP, 0.6 is assessed as digestible true protein, 0.15 being regarded as nucleic acids and 0.25 as indigestible microbial cell wall (Russell *et al.* 1992).

The other component of DPLS is the truly digestible UDP, DUDP, and the two functions below are **adopted** here for its prediction. For forages, DUDP is estimated by equation 2.18, a modification of an equation of Webster *et al.* (1982). This predicted value has a lower limit of 0.05, and an upper limit of 0.85 that is reached when forage CP is 187 g/kg DM or greater. For concentrate supplements, DUDP is calculated from its acid-detergent insoluble protein (ADIP, g/kg DM), with equation 2.19, based on Waters *et al.* (1992).

$$\text{DUDP} = \text{UDP}(0.0055\ \text{CP} - 0.178) \tag{2.18}$$

$$\text{DUDP} = \text{UDP}(0.9(1 - (\text{ADIP}/\text{UDP}))) \tag{2.19}$$

Net protein requirements of the animal

The minimum (maintenance) requirement

The minimum requirement is the quantity of protein that will counterbalance the inevitable urinary, faecal and dermal losses of N and thus maintain tissue proteins. As noted on p. 14, the maintenance of body protein is not coincident with energy maintenance; it is usually found that when energy retention is zero there is a positive, though small, N balance in the animal.

The ARC (1980) assessed the minimum requirement as a dermal protein loss in hair and scurf by cattle or in wool by sheep, plus an endogenous urinary loss (EUP) that was related to live weight with separate equations for cattle and sheep. No allowance was made for an endogenous faecal loss (EFP) on the grounds that much of the loss resulted from an inefficiency in the absorption of MCP, which was assumed to be mainly exogenous in origin. It was also considered that that there was no method by which the component of EFP that was truly endogenous could be determined.

The amended approach of the ARC (1984) used the same estimates of dermal loss, and allowed for EFP as well as EUP because both losses were considered to be part of the protein requirement. The urinary and faecal losses were not to be assessed separately, but were regarded as total endogenous nitrogen (TEN). The value adopted by ARC (1984) was 0.35 g TEN/kg $W^{0.75}$, which is used at all levels of feeding though stated to be applicable 'at a maintenance level of metabolisable energy intake'. This approach, which was continued by AFRC (1992) although the component is now described as basal endogenous nitrogen (BEN), implies that for any increase in EFP with increasing intake, there is a corresponding reduction in EUP. The estimate of BEN was based on studies made by E. R. Ørskov and colleagues with animals nourished by intragastric infusions. Animals so nourished do not have a normally functioning rumen because they lack a truly functional microbial population.

Consequently there is virtually no conservation of protein by microbial capture of N recycled to the rumen and the value of 0.35 g BEN/kg $W^{0.75}$ may well overestimate the minimum protein requirement of normally fed animals. Consider, for example, a situation not uncommon in Australia: a steer of, say, 200 kg surviving on a poor-quality dry pasture with a DMD of 0.53

and (equation 1.12A) M/D = 7.4. In these conditions it might eat 4.2 kg DM/d (Chapter 6), yielding about 30 MJ of ME, which is less than its requirement for maintenance (Chapter 1), and potentially yielding 141 g microbial DPLS (Table 2.5; see p. 100). With a 0.75 efficiency of use of the DPLS by the tissues (ARC 1980), the net protein gain by the animal of 106 g would barely provide for a total endogenous loss of 116 g/d (i.e. $6.25 \times 0.35 \times 200^{0.75}$).

However, 141 g microbial DPLS would require an RDP supply of 235 g that would be provided by a minimum of 56 g CP/kg pasture DM only in the unlikely event that the CP was wholly degraded in the rumen. Undegraded dietary protein would not make up the probable shortfall in RDP and the resulting DPLS, and though the animal could still survive and perhaps maintain its DMI with the aid of recycled N, it is evident the ARC (1984) estimate of 0.35 g TEN/kg $W^{0.75}$ implies the onset of a serious protein deficiency in animals even when their forage contains much more CP than the amounts commonly present in dry pastures.

Thus the AFRC (1992) estimate of a BEN loss is not adopted here, where the estimate of the minimum requirement makes allowance for EFP, as well as the EUP and dermal losses, for reasons that are explained below.

Endogenous urinary loss (EUP)

Folin (1905) introduced the concept of dividing urinary N excretion into two components: (*a*) a relatively constant component termed endogenous urinary nitrogen (EUN) representing the minimum losses arising from inefficient recovery of N compounds turned over in the body and from irreversible reactions such as conversion of creatine to creatinine, and (*b*) an exogenous component arising from the metabolism of absorbed protein and of tissue protein involved in reversible biochemical reactions. The distinction between (*a*) and (*b*) is difficult to define precisely. The EUN includes urea, creatinine, bilirubin, allantoin, hippuric acid, uric acid and amino acids such as 3-methyl-histidine, and is assumed to be the minimum urinary N excretion of an animal maintained for an extended period on a diet that contains little or no protein, but is adequate in energy and other nutrients.

Brody (1945) found that EUN for a very wide range of animal species was related to basal metabolic rate, the general value being 2 mg EUN/kcal (about 0.5 mg/kJ), and hence was 0.141 g EUN/kg $W^{0.734}$ per day. Swanson (1977) analysed data for cattle and calves only and reported EUN g/d = 0.43 kg $W^{0.505}$. This relationship predicts EUN excretions rather similar to those estimated by Brody (1945) for W up to 150 kg, and then progressively lesser amounts (e.g. 9.9 g/d *v.* 13.5 g/d respectively at W = 500 kg); the predictions more closely resemble those made with the equation 2.20 based on ARC (1980) and here expressed as EUP (i.e. EUN × 6.25). This equation predicts lower values than those from the CNCPS function 2.75 $W^{0.5}$/0.67 (Fox *et al.* 2004).

$$\text{EUP g/d (cattle)} = 16.1 \ln W - 42.2 \quad (2.20)$$

Equation 2.20 is **adopted** here for *B. taurus* cattle breeds. There is evidence (see ARC 1980) that EUN excretion is lower in *B. indicus* breeds, and for these it is **proposed** the values predicted with equation 2.20 be reduced by 20%.

The ARC (1980) equation for sheep, also **adopted** here, is:

$$\text{EUP g/d (sheep)} = 0.147 W + 3.375 \quad (2.21)$$

This equation, like 2.20, yields lower values than that of Brody (1945). Because a significant fraction of the EUP may be derived from N compounds other than amino acids (Owens 1987),

this requirement will not have to be supplied wholly by DPLS. However, it may be assessed in these terms by assigning a value for the efficiency of conversion of DPLS to EUP (see p. 95) from the upper part of the range of estimates of 0.47–1.0 used in various protein systems (NRC 1985*b*).

For goats, Sahlu *et al.* (2004) reported a mean value for EUP of 1.03 g/$W^{0.75}$.

Endogenous faecal loss (EFP)

As implied by the AFRC (1992) use of BEN, the faecal and urinary endogenous losses are not wholly distinct one from the other. Ørskov *et al.* (1970) showed that when fermentation in the hind-gut was increased by infusion of starch into the caecum there was an increase in faecal N excretion and a reduction in urine N. It is uncertain whether such a change alters total N loss, but it does illustrate that the so-called metabolic faecal nitrogen (MFN) is a complex entity with origins that are not well defined.

All the MFN would be endogenous if the animal ate an N-free diet, but this state is impracticable with ruminants. A long period elapses before faecal N excretion falls to a baseline (Swanson 1977) because recycling of N to the rumen and large intestine continues to provide some N for microbial activity.

Some of the MFN consists of materials such as sloughed epithelial cells, mucous secretions and bile pigments, which are unequivocally endogenous. These materials would have been major contributors to the faecal N excretions measured by Ørskov and Macleod (1982) and Storm *et al.* (1983*a*) with animals maintained by essentially N-free intragastric infusions. With cattle the mean daily excretion was 0.026 g N/kg $W^{0.75}$ and if it is assumed that a maintenance intake of solid feed would have been 50 g DM/kg $W^{0.75}$ the corresponding estimate of MFN is 0.52 g/kg DMI. With sheep the mean excretion in faeces was 0.036 g N/kg $W^{0.75}$, and with an assumed maintenance DMI of 40 g/kg $W^{0.75}$this is equivalent to 0.9 g N/kg DMI.

These values are much less than the estimates of the MFN excretion by normally fed animals, which is found to be positively related to DMI, and the most common method of estimation is from the regression of g faecal N/kg DMI on g N intake/kg DMI. The results generally obtained indicate MFN is of the order of 5 g/kg DMI (31.3 g CP). Similar values are obtained from regression analyses of data on the CP and digestible CP contents of feeds. For example, Holler and Reid (1959) found that the DCP content of a wide range of forages (g/kg DM) could be predicted with the equation (0.929 g CP/kg DM – 34.8). This equation indicates that the true digestibility of the CP in these feeds is about 0.93, and that with zero CPI, 34.8 CP (5.6 g MFN) will be excreted per kg DMI. A summary of 20 regression equations of this type for many feeds, reported by Owens (1987), indicated DCP = 0.89 CP – 30.7; thence, with 4.9 g MFN (30.7 g CP) per kg DMI the apparent digestibility of CP would fall to zero at 34.5 CP/kg feed DM.

In most instances the majority of faecal N is not undigested feed CP but to a substantial extent, probably exceeding 50% (Mason 1969), is present in microbial debris from the rumen and large intestine. From regression analysis of measured N flows in cannulated sheep given 13 forages differing widely in nutritional value, Hogan and Weston (1968) concluded that of the estimated 4 g MFN excreted per kg OMI, 1.8 g originated in the small and large intestines. This value of 1.8 g MFN/kg OMI is within the range often reported for non-ruminants, and Hogan and Weston (1968) concluded that the higher MFN excretions in ruminants reflect ruminal fermentation. In their studies this fermentation appeared to contribute 3.8 g MFN to the total of 4 g/kg OMI and it was presumed to be mainly in the form of undigested rumen microbial CR.

Subsequent studies with ^{15}N-labelled rumen micro-organisms (RMO) by Salter and Smith (1977) and Siddons *et al.* (1985) and with intragastric infusions of RMO (Storm *et al.* 1983*b*) indicate, however, that more than 0.8 of the N in RMO is digested in the intestines. Judson *et al.* (1975), who infused ^{35}S-labelled RMO into the caecum, found 0.42 was digested in the large intestine alone. Consequently it appears that although some of the MFN originates from the rumen, a proportion of this may consist of keratinised cells sloughed from the epithelium and undigested salivary and gastric secretions. It also appears that the large contribution of microbial material to MFN (Mason 1969) originates mainly from microbial growth in the large intestine.

It is likely that the N sources for this growth are mostly endogenous because the amount of fermentable dietary N remaining in this part of the alimentary tract is likely to be small. One source is endogenous urea (Dixon and Nolan 1983). Its use by the micro-organisms represents a protein cost to the animal to the extent that the urea originates from the catabolism of body protein and that it could otherwise have been transferred to the rumen and promoted MCP synthesis. Non-urea sources, which more directly represent a protein cost, include the proteins in epithelial cells sloughed from the caecum itself and from elsewhere, and the variety of secretions into the alimentary tract.

The information that has been reviewed leads to the conclusion that some of the non-dietary CP excreted will have originated from exogenous N but to assume, as in the ARC (1980) system, that the origins are wholly exogenous is to ignore the evidence that EFP is also derived from endogenous N. An allowance must be made for this endogenous loss in EFP when assessing the protein requirements of the animal.

An allowance for EFP in terms of a net protein requirement has been assessed in two ways. One approach (J. V. Nolan unpublished data) was to examine the available information on the quantities of nitrogenous materials entering successive sections of the alimentary tract and to estimate the proportions of the N that could be recovered by the animal in the form of amino acids. By this means it was estimated that the net loss of protein in faeces was approximately 18 g/kg DMI. The second approach was made by Hulme *et al.* (1986) in the development of their CAMDAIRY model of dairy cow nutrition. It is generally recognised (e.g. Webster 1987) that the ARC (1980) estimates of dietary protein requirements are unrealistically low, and Hulme *et al.* (1986) ascribed this to the nil allowance for EFP and possible overestimation of the efficiency of use of DPLS by the animal. They accepted as realistic the NRC (1978) estimates of protein requirements for dairy cattle because they were substantially confirmed by the results of feeding trials. One means by which the CAMDAIRY protein allowances were made similar to the NRC (1978) estimates was by the inclusion of an allowance for EFP of 15.2 g/kg DMI. This value for EFP is **adopted** here.

$$\text{EFP} = 15.2 \text{ g/kg DMI} \tag{2.22}$$

Varying the EFP component of the minimum protein requirement with DMI is consistent with the results of the many studies of MFN excretion, and the allowance is more simply assessed in practice on this basis than on faecal DM output that might be preferred with some types of diet (Swanson 1982). The NRC (1985*a*) and the CNCPS (Fox *et al.* 2004) assess EFP as 90 g/kg indigestible dry matter (IDM), the IDM in the diet being estimated as (1–TDN) where the TDN (Total Digestible Nutrients) content used is 0.92 of the value reported at a maintenance level of feeding. The EFP value adopted here would be the same as that of the CNCPS if diet DM digestibility were about 0.83 but appreciably lower on diets of low digestibility, e.g. 76 g *v.* 225 g for DMI 5 kg of a diet of 0.5 DMD.

An increase in the rate of net protein deposition in the body promoted by increased feed intake is associated with an increase in tissue protein turnover, i.e. higher rates of both protein synthesis and protein degradation (Nolan 1987). Information reviewed by Webster (1980) supports the view that as degradation rate increases there will be an increase in the amount of endogenous protein entering the alimentary tract from gut tissue itself and, probably, from the other body tissues. There is unlikely to be a corresponding increase in the efficiency of protein absorption, and so there will be an increase in the faecal loss of endogenous protein. Thus the variable allowance for EFP makes an allowance for what, essentially, is a variation with level of feeding in the maintenance requirement for protein.

For goats, Sahlu *et al.* (2004) reported a mean value for metabolic faecal protein of 26.7 g/kg DMI but AFRC (1998) concluded that there is no compelling evidence that the maintenance requirements for goats differ appreciably from those for cattle and sheep.

Dermal loss

(*a*) *Cattle*. The estimate of ARC (1980) is **adopted**:

$$\text{Dermal protein loss per day (cattle)} = 0.11 \text{ g/kg } W^{0.75} \tag{2.23}$$

Sahlu *et al.* (2004) estimated mean dermal protein loss in goats at 0.2 g/kg $W^{0.6}$.

(*b*) *Sheep*. Sheep continue to grow wool even when chronically undernourished and this causes an inescapable and irreversible loss of amino acids that will always exceed the loss per unit live weight from the skin of cattle. Estimates of requirements are given below.

Gestation

The equations of the ARC (1980) for estimating the quantities of protein deposited in the foetus and the gravid uterus are **adopted** here. As with the equations for predicting energy gains (see p. 33), the coefficients have been adjusted so that predictions are consistently on the basis of natural logarithms and are scaled in relation to the birth weights specified by the ARC.

$$Pr = SBW \exp(A - B \exp(-Ct)) \tag{2.24}$$

where Pr is the protein content (g for sheep; kg for cattle) of the foetus or gravid uterus at time t (days) after conception and SBW is the scaled birth weight, i.e. the ratio of the expected birth weight to the specific weights of ARC (1980): 4 kg for a lamb at 147 d gestation or 40 kg for a calf at 281 d.

By differentiation:

$$dPr/dt = Pr[B\ C \exp(-C\ t)] \tag{2.25}$$

The gravid uterus coefficients set out below are used to predict the total net protein requirements for pregnancy though, as for energy, there may be insufficient allowance for the production of colostrum towards the end of gestation (Mellor and Murray 1985; Robinson 1987). The predicted values are adjusted pro rata for total birth weights of twins etc.

		A	B	C
Sheep:	Foetus	8.241	21.190	0.01704
	Gravid uterus	11.347	11.220	0.00601
Cattle:	Foetus	5.358	15.229	0.00538
	Gravid uterus	8.536	13.120	0.00262

There is little information available for goats and the sheep equation could be used for this species, as is suggested by AFRC (1993) and Sahlu *et al.* (2004).

The additional need for protein by ewes during the last three weeks of gestation and the first 6–7 weeks of lactation, to counter the periparturient relaxation of immunity to gastrointestinal nematode infection is discussed on p. 228.

Weight change

The prediction of the protein content of empty body gain (EBG) and thus the net protein requirement for gain in immature animals, described on p. 34 with equation 1.31, is **adopted** here.

$$\text{Protein (g/kg EBG)} = (212 - 4R) - (a - 4R)/[1 + \exp(-6(Z - 0.4)))] \quad (1.31)$$

where:

a = 120 for large lean beef cattle breeds, e.g. Charolais, Chianina, Limousin, Maine Anjou and Simmental; = 140 for all breeds of sheep, and all other breeds of cattle;

Z = current W/SRW, with a maximum value of 1.0 when the animal reaches maturity;

R= adjustment for rate of gain or loss = (L–2) where L is the level of feeding: MEI/ME_m.

It is assumed that EBG = 0.92 LWC. Predicted values for the protein content of EBG at various stages of growth (P) at two rates of gain (R) are shown in Table 1.13.

For mature animals, equation 1.34 or 1.34A is **adopted** for predicting the protein content of empty body weight change (kg/kg) as a function of relative body condition or condition score, respectively.

The same method of prediction can be used for goats if appropriate SRW are identified.

Milk production

The majority of the N in milk, 0.95 or more, is present in proteins and the ARC (1980) approach is **adopted** here, with the net protein requirement for milk production assessed as 6.38 × (total N – NPN). This is because the NPN secreted is mainly waste products of N metabolism, including urea, creatine, creatinine and uric acid, which would otherwise have been excreted in urine.

However, excluding NPN from consideration will have little effect on estimates of the total protein requirements of lactating animals. The Kjeldahl method determines total N, and the values so obtained may be used as such if no others are available or, if desired, they may be adjusted by subtracting an assumed NPN concentration of 0.30 g N/kg milk. On the other hand, modern analytical methods used in the quality control of milk directly determine proteins.

Cattle

There is a genetic correlation between the fat and protein contents of milk; for example the concentrations of both constituents are higher in the milk from Channel Island breeds than in that from Friesians. If there is no direct information on protein content (g/kg), it may be predicted from the fat content (g/kg), if this is known, with the equations of Gaines and Overman (1938). These equations have been adjusted by the ARC (1980) to predict protein N rather than total N and, multipled by the factor 6.38, they are:

Ayrshire milk	MP = 20.67 + 0.30 F	(2.26A)
Holstein–Friesian milk	MP = 13.21 + 0.53 F	(2.26B)
Guernsey milk	MP = 6.76 + 0.59 F	(2.26C)
Jersey milk	MP = 12.97 + 0.44 F	(2.26D)

where MP is milk protein g/kg, and F is milk fat g/kg.

Sheep

Values for the total N content of milk from ewes of many breeds and at various stages of lactation were reviewed by the ARC (1980) and, after assuming 0.55 g NPN/kg, it adopted a weighted mean value of 48.9 g protein/kg. Corbett (1968) showed that protein concentration increases during the course of lactation, as in cow milk, and the unweighted mean for grazing Merino ewes during weeks 2–6 of lactation (again assuming 0.55 g NPN/kg) was 47.3 g protein/kg. Other values, excluding NPN, for grazing Merinos are an average during weeks 2–6 of lactation of 39.2 g protein/kg (Peirce 1936), and 43.4 g protein/kg in week 4 (Brett *et al.* 1972).

With housed Merino ewes the mean concentration during the first nine weeks after lambing was 42.4 g protein/kg (Oddy 1985).

It is suggested that 45 g protein/kg ewe milk be assumed when actual values are not available. If this is an underestimate for the later stages of lactation, the error in an estimate of protein requirement will be small because milk yield, and milk protein g/d, will then generally be low relative to peak production.

Goats

The energy content of goat milk resembles that of the cow more closely than that of the ewe (Morand-Fehr *et al.* 1980; Sahlu *et al.* 2004), and the same is true of protein concentration, which is rather similar to that in the milk from Holstein–Friesians. Accordingly a mean protein concentration of, say, 32 g/kg milk can be assumed or, if fat content is known, it could be predicted with equation 2.26B.

Wool growth

The net protein requirement is the rate of growth of clean wool fibre because this is unequivocally protein, but with an amino acid composition different from that of most other body proteins, containing a higher proportion of sulfur-rich amino acids. This has consequences for the estimation of dietary requirement (see below).

AFRC (1993) retained the ARC (1980) functions for relating the quantity of protein retained in wool by growing sheep of British breeds to the protein gain in their fleece-free body. It also assumed that pregnant and lactating ewes synthesise 5.3 g wool protein/d but did not suggest a value for adult, non-breeding sheep.

The method **adopted** in this Report to estimate the net protein requirement for wool growth was described by Freer *et al.* (1997) and Nagorcka and Freer (2005). Daily growth of clean wool (g/d) is predicted (equation 2.27) either from the DPLS available for wool production, $DPLS_w$ (i.e. after deducting the needs for gestation and lactation), or from the ME similarly available for wool production, ME_w, whichever is limiting. For a range of data from Merino sheep with an average annual greasy fleece weight (SFW, kg) amounting to about 0.1 SRW, Hogan *et al.* (1979) estimated a mean gross efficiency of 0.116 for the conversion of absorbed amino acids to wool.

Kempton (1979) pointed to the importance of the balance of protein and energy in the absorbed nutrients and concluded from a review of experiments with Merino sheep that a protein to energy ratio of 12 g/MJ ME was required for maximum wool growth. It follows that if the ratio is less than 12, wool growth is dependent on DPLS and above 12 it is dependent on MEI, i.e. for the average Merino, the limit is set by 0.116 * 12 ME_w = 1.4 ME_w. Efficiency of conversion is scaled for other sheep, or for treatments such as supplementation with 'protected' sulfur-rich amino acids (e.g. Mata *et al.* 1995), by using the appropriate ratio of SFW to SRW. It is also scaled for day length effects (*DLF*) that are specific to the breed (Nagorcka 1979) and in young lambs it is scaled (*AF*) for the delayed maturation of secondary wool follicles (Lyne 1961).

$$\text{Wool growth} = \frac{SFW}{SRW} AF\ DLF \min(1.16 DPLS_w, 14 ME_w) \quad (2.27)$$

where:

$AF = 0.25 + 0.75(1 - \exp(-0.025A))$, where A is age in days;

$DLF = 1 + c(DL - 12)$, where DL is day length in h;

selected values for c are: Merinos 0.03; Corriedale, Romney 0.06; BL × Merino 0.07; Border Leicester, Dorset 0.11.

The effect of the balance between $DPLS_w$ and ME_w in determining wool growth is illustrated in Fig. 2.2. Solutions to equation 2.27 for sheep of different wool-growing potential (i.e. SFW) are shown in Table 2.4.

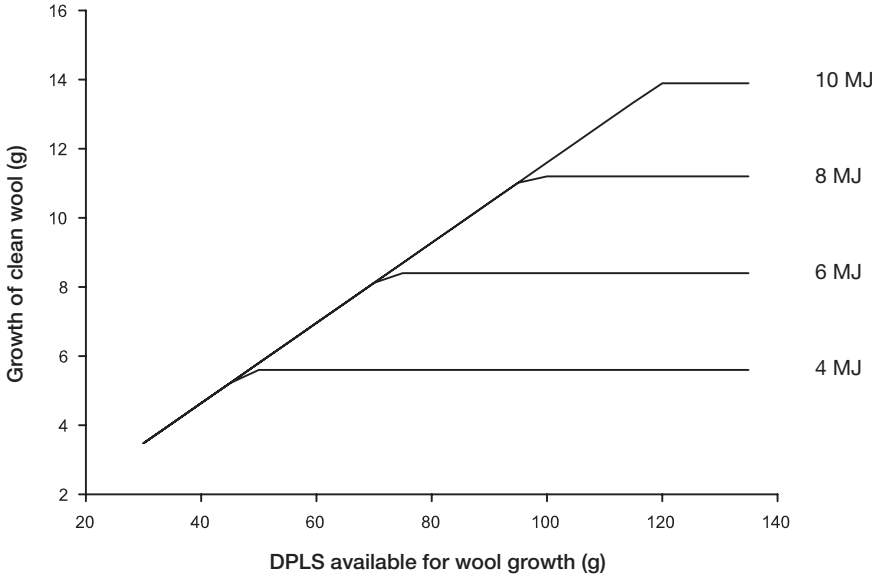


Fig. 2.2. Predicted growth of clean wool from a mature Merino ewe with a standard reference weight of 50 kg and a standard fleece weight of 5 kg in relation to DPLS available for wool production at four levels of ME available for wool production: 10, 8, 6 and 4 MJ/d.

The adjustments made in estimating $DPLS_w$ and ME_w are designed to match the information reviewed by Corbett (1979), which showed that the full cycle of reproduction in ewes reduces annual fleece growth by 10–14% compared with those non-breeding. Wool growth may be reduced by up to 30% during the last two months of pregnancy and by up to 50% during

lactation. In sheep losing weight (see p. 98), protein released from catabolised tissue contributes to $DPLS_w$ and hence to wool growth (Revell *et al.* 1999).

In the absence of specific information, protein requirements for wool production from goats may be predicted in the same way, using appropriate values for SFW and SRW.

Table 2.4. Estimates of the growth of clean dry wool (g/d) by non-pregnant, non-lactating adult sheep having various ratios of Standard Fleece Weight (SFW) to Standard Reference Weight (SRW), in response to intake of DPLS at a constant MEI of 10 MJ/d. See text for definitions and adjustments for ages less than about three months and for pregnancy and lactation

SFW:SRW	DPLS (g/d)			
	50	75	100	125
0.06	3.5	5.2	7.0	8.7
0.08	4.6	6.2	9.3	11.6
0.10	5.8	8.7	11.6	14.5
0.12	7.0	10.4	13.9	17.4

Dietary protein requirements

Efficiency of use of DPLS

Maintenance, weight change, gestation, milk production

The uncertainty about the efficiency with which absorbed amino acids are used by the animal is illustrated by the range of values used in various protein systems (Alderman 1987). It cannot be supposed that any single value, or range of fixed values, will be reliable. Maximum efficiency in the use of absorbed amino acids is likely to occur when protein is the first limiting nutrient. However, protein is used by tissues as individual amino acids and high efficiency is possible only when the relative amounts of amino acids in the pool available for metabolism correspond closely with the quantities that are required concurrently by the tissues. If one or more amino acid is limiting, the efficiency of use of the remainder will be reduced, and the efficiency of use of all could be reduced if the supply of protein is in excess relative to the supply of ME or other nutrients.

AFRC (1992, 1993) has adopted a range of efficiency values for the use of DPLS: 1.00, 0.59, 0.85, 0.68, 0.26 for maintenance, growth, pregnancy, milk production, and wool growth respectively, but admits that support for these values is somewhat flimsy. In this Report we continue to take the view that there is no clear, well-founded alternative to the application of a single value for the efficiency of DPLS use by the animal for all purposes, except for wool growth. Following the approach of Hulme *et al.* (1986), discussed in the section on EFP above, an efficiency of 0.70 is **adopted** here for the use of DPLS for EUP and EFP, for the dermal loss by cattle (but not by sheep), and for growth and milk production, rather than the less conservative 0.75 proposed by the ARC (1980). A net efficiency of 0.7 is also adopted for gestation.

Wool growth

Wool protein differs from other body proteins particularly because of its high content of sulfur-rich amino acids (SAA), predominantly cystine. For example, Marshall and Gillespie (1977) reported that SAA comprised about 0.14 of the total amino acids in wool fibre, which is three to four times the SAA concentration in milk and meat proteins. It is also three to four times the

SAA concentrations usually found in absorbed amino acids. Lindsay *et al.* (1980), for example, reported that only 0.035 of the amino acids actually absorbed by sheep from forage diets were SAA.

There are many reports of increased wool growth in response to additional SAA provided as supplements protected from ruminal degradation or administered parenterally (Reis 1979), confirming expectation that they are first-limiting. In consequence, it can be expected that because there will be substantial excesses of non-limiting amino acids in the total supplies available for the synthesis of wool proteins, the overall efficiency of use of DPLS for wool synthesis will be low.

From the estimate of about 0.12 as the gross efficiency of conversion of absorbed amino acids to wool protein (Hogan *et al.* 1979), a net efficiency value can be derived by excluding from the denominator the amounts of truly absorbed amino acids assumed to have been used for protein maintenance by the sheep and, because intakes were generally above maintenance, for body protein gain. With further adjustment to expression as DPLS, values of 0.20–0.25 for its conversion to wool protein can be calculated. An alternative method of estimation is possible: the value adopted for the conversion of DPLS to body proteins with similar amino acid composition is 0.7, but because the SAA concentration in wool protein is around 3.5 times that in the DPLS from many diets, an efficiency of conversion to wool of 0.2 is indicated.

Further information is provided by Reis and Schinkel (1964) who reported that the infusion of 60 g casein/d into the abomasum increased clean wool growth by 6.7 g/d. The SAA supplied, as cysteine equivalent, was about 1.7 g/d and on this basis its proportional contribution to total amino acids infused was similar to the SAA concentration in the protein from duodenal digesta reported by J. P. Hogan *et al.* (1968). The addition of 3.0 g cysteine to the daily infusion of casein increased clean wool growth by, on average, a further 2.5 g/d. If the apparent digestibility of these additions to PLS is assumed to be 0.7, there was a recovery in the wool of 0.16 of the amino acids in the casein (42 g DPLS/d) and 0.21 of those in the casein plus cysteine (44 g DPLS/d).

It should be noted that these estimated conversions are not net efficiencies because: (*i*) they do not take account of the use of the additional absorbed amino acids for purposes other than wool synthesis; (*ii*) though the addition of cysteine to the casein increased the cysteine equivalent content to about 0.08 this is still lower than the content in wool; and (*iii*) the cysteine infusion is likely to have increased the synthesis of high-S wool proteins (Reis 1979) so that the actual wool growth response (g/d) may have been less than if composition was unaltered.

Although the net (i.e. partial) efficiency of conversion of DPLS to wool may well be of the order of 0.2, it is inappropriate to use this value in the factorial assessment of the total protein requirement of the animal. If it were used, it would be calculated that the notional fraction of the total DPLS requirement that was used specifically for wool growth was an amount equal to five times the amount of wool protein synthesised. It would be assumed that 0.8 of this fraction was unused for any other purpose and was eliminated by excretion. However, the DPLS used for wool growth is drawn from the same pool in the body as that used for other purposes and, as part of that pool, the notional 0.8 residuum makes some contribution to protein nutrition. To ignore such contribution would introduce some double accounting into the factorial assessment, because full allowance will have been made for the DPLS requirements for EUP, EFP, growth, gestation and milk.

The special demand for SAA for wool growth can be perceived as causing a reduction in the proportion of SAA in the total DPLS pool and, consequently, reducing the biological value for other purposes of the pool. Ideally, a single value would be used to describe the efficiency of use

of DPLS by a sheep as a whole. The value would be set at less than 0.7 to an extent that varied with the rate of wool growth in absolute terms and as a proportion of total DPLS use for all purposes. No ready means for achieving this has been devised and the approach **adopted** in this Report is to specify a partial efficiency of 0.6 for the use of DPLS for wool growth in contrast to 0.7 for other purposes. Thus:

DPLS g/d for wool = (clean wool g/d)/0.6

Nitrogen recycling

No explicit allowance is made in this Report for the transfer of endogenous N to the rumen (recycling), which occurs by way of saliva and by diffusion through the rumen wall and promotes the conservation of N that would otherwise have been part of the EUP. Consequently the EUP excretion by ruminants is relatively less than that by non-ruminants in which recycling, in the absence of coprophagy, is unimportant in the protein economy. There is thus some implicit allowance for recycling from the use of equations 2.20 for cattle and 2.21 for sheep to estimate EUP, which do predict lower values than those applicable to non-ruminants.

Prediction of the rate of endogenous N transfer to the rumen is difficult, as is evident from the discussion of this matter by the NRC (1996). In general, urea transfer is directly related to the plasma urea concentration. This affects the concentration in saliva (Somers 1961*b*), where urea accounts for 0.6–0.7 of the total N content (Somers 1961*a*), but the actual amount of N entering the rumen by this route will vary with the rate of saliva secretion. With forage diets, Hogan (1982) estimated that saliva could supply from 1–8 g N/d in sheep and 6–28 g N/d in cattle. This supply could exceed the amount of urea N entering the rumen by diffusion from blood, particularly in animals eating forages (Kennedy 1980). In cattle, the rate of urea transfer from blood to rumen was found to vary with plasma concentrations of urea N up to about 100 mg/l (Thornton 1970*a*) or 120 mg/l (Vercoe 1969*a*); in the latter study, where the hay diet had a DMI of 0.47 and contained 69 g CP/kg DM, the transfer was estimated as 17–20 g urea N/d. Nolan *et al.* (1987) estimated there was a transfer of 11 g urea N/d in cattle eating a mature sub-tropical grass hay (52 g CP/kg DM).

In sheep, Weston and Hogan (1967) and Thornton (1970*a*, 1970*b*) found that urea transfer continued to a higher limiting plasma concentration in the range of approximately 150–180 g urea N/l and was at a maximum rate of about 5 urea N/d. Nolan (1975) estimated a transfer of 1.3 g urea N/d in sheep given lucerne chaff at hourly intervals throughout the day. However, there is evidence from both cattle (Norton *et al.* 1979; Kennedy 1980) and sheep (Norton *et al.* 1978) given forages that there is a less close association in the rumen than in the post-ruminal part of the digestive tract between the rate of diffusion of urea and the plasma concentration. One reason for this may be the variability in the ruminal ammonia concentration. While urea appears to diffuse readily when the ammonia concentration is low, it does so less readily as the concentration increases and ceases when there is about 200 mg ammonia N/l ruminal fluid (Kennedy and Milligan 1980). The ammonia is itself absorbed through the rumen wall into the blood at rates that depend on the non-ionic ammonia concentration, the latter being a function of the total ammonia concentration and rumen fluid pH (Siddons *et al.* 1985) and SCFA movements through the rumen wall (Bodecker *et al.* 1990). Some absorption occurs even when rumen concentrations are very low, and the amount and direction of the net flux of N between blood and rumen is thus determined by the rate of ammonia absorption as well as by the diffusion of urea in the reverse direction.

Ruminal ammonia concentrations vary with the animal's diet and its pattern of feed intake. The concentrations, and the overall N economy, also vary with the type and physiological state of the animal. For example, the assumption (see p. 87) that EUP with *B. indicus* breeds is 0.8 of that with *B. taurus* is consistent with the observations by Hunter and Siebert (1985) and Hennessy (1987) of higher plasma urea and ruminal ammonia concentrations in Brahman cattle than in Herefords of similar live weight that were eating similar amounts of low-quality roughage (36 g CP/kg DM). This difference can be interpreted as a superior ability of the Brahmans to recycle N to the rumen. It can also be linked with voluntary water intakes, which tend to be lower with *B. indicus* than *B. taurus* (Chapter 5). Vercoe (1967, 1971) found that water intake was negatively correlated with plasma urea concentration and N balance, and positively correlated with the urinary excretion of total N, creatinine and uric acid. Both Payne (1963) and Ikhatura *et al.* (1985) reported that restriction or deprivation of water increased the N balance in cattle given poor roughage (40–50 g CP/kg DM). No increase has been reported in sheep (Bohra and Ghosh 1977; Obitsu *et al.* 2000) on either poor- or high-quality diets.

Urinary N excretion is increased when rectal temperature increases (Vercoe 1969*b*; Vercoe and Frisch 1970; Vercoe *et al.* 1972), and in addition to an effect of increased water intake in these conditions, there is evidence of increased protein catabolism. Heat stress, indicated by an elevated rectal temperature, occurs at higher ambient temperatures in *B. indicus* than in *B. taurus* cattle and the greater heat tolerance of the former is of benefit in their N economy.

In addition to endogenous urea transfer, other endogenous N enters the rumen in salivary proteins and as rumen wall sloughings or rumen epithelium digested by local populations of bacteria.

It is evident from the preceding discussion that an explicit allowance for N recycling cannot readily be defined. A practical alternative that is appropriate when, as in the recommendations in this Report, the intention is to provide for the long-term sustenance of the animal, is to assume that an inadequacy or inefficiency of capture of N from RDP is, in the short term, approximately compensated by the recycling of N into the rumen, albeit at a reduced level of feed intake (see Chapter 6). While recycling can offset intermittent inadequacies of RDP, it will not continue to do so throughout a chronic inadequacy of dietary protein. Supplementation with NPN or protein, as appropriate (see below), will increasingly become necessary even for survival (Nolan and Dobos 2005).

Protein contributions from liveweight loss

Even when well fed, lactating animals generally lose live weight early in lactation. Energy from this loss is used for milk production (see p. 40), and the catabolism of body tissues will also release amino acids into the bloodstream. The NRC (1985*a*) assumes that 1 kg loss in EBW by lactating cows yields a quantity of amino acids equivalent to 160 g truly absorbed protein, whereas AFRC (1993) uses a value of 138 g/kg liveweight loss. Neither the latter report nor any other gives consideration to the consequences of liveweight losses during periods of undernutrition, which are important episodes in animal production systems in many parts of Australia.

Amino acids becoming available from catabolised tissues will be indistinguishable in the body from those that have been absorbed from the gut. There is likely to be some wastage of amino acid N in the forms of 3-methyl-histidine, creatine, creatinine and other products of catabolism, and the NRC (1985*a*) assumes values for efficiency of use of mobilised tissue proteins that are the same as those it assumes for the use of truly absorbed amino acids (see p. 95).

When animals are losing weight, for example, those grazing poor-quality forage with low CP content, the N from catabolised tissues can enter the rumen as urea and decrease the dietary deficit of RDP. Information is scant on the efficiency of transfer of body protein N to the rumen and its incorporation into MCP. In a study of N dynamics in penned Merino sheep (33 kg W) made by Nolan and Stachiw (1979), the intakes of low-quality feed (0.51 OMD, 238 g DOM/d, 38.8 g CF/d) maintained animal live weights and a small positive N balance (0.4 g/d); it was estimated that 4.1 g/d of endogenous urea N was transferred to the digestive tract of which 2.3 g N/d (i.e. 14.4 g RDP/d) was transferred to the rumen. If the RDP requirement is estimated as (0.238 × 130) g/d and only 0.6 of the dietary CP was degraded, the urea transfer would have eliminated the deficit of about 8 g RDP/d. In the study of Neutze *et al.* (1986), the mean intake of the sheep (35–45 kg W) given alkali-treated straw with OMD = 0.60 was 0.43 kg DOM/d; this provided 44.4 g CP/d, of which 26.9 g was in the form of urea, and resulted in a positive N balance of 0.9 g/d. It was estimated that the transfer of urea N from blood to the rumen was equivalent to an additional 23.8 RDP/d, but it appeared that only 0.55 of this was incorporated into MCP.

With still lower CP in the diet and substantial loss in live weight there could be a higher rate of endogenous urea transfer, but in 200 kg cattle eating hay (52 g CP/kg DM) Nolan *et al.* (1987) found that of 11 g urea N/d recycled to the rumen nearly one-half (5.3 g N/d) was lost by absorption or passage of ammonia from the rumen and was not available to the microbes. Sriskandarajah *et al.* (1982) gave Hereford heifers (18 months old, average 209 kg W) chaffed wheat straw (31 g CP/kg DM) plus supplements containing urea and varying proportions of casein or formaldehyde-treated casein that increased the CP content of their diets to about 150 g CP/kg DM. When the supplements were withdrawn after five weeks, the intakes of straw, which had averaged 3.1 kg/d, remained essentially the same throughout the following eight weeks at 3.2 kg/d, but the animals lost live weight at a mean rate of 157 g/d. From studies on the N transactions in similar animals it was concluded that the endogenous contribution to RDP was about 80 g/d, but only about one-third of this could have originated from the protein in the tissues catabolised at a rate seen as a loss in W of 157 g/d.

Even if the efficiency of transfer of tissue N to MCP were 1.0, this process could only make good a rather small deficiency of dietary RDP. If, for example, a 250 kg steer grazing poor pasture were losing 0.5 kg W/d, this could provide about one-quarter of its net energy requirements for maintenance of, say, 27 MJ/d after allowing for the energy cost of grazing and assuming that NE_m was reduced to about 0.85 of the requirement of an animal not in a survival situation. Body protein loss would be around 80 g/d, and if wholly transferred to the rumen and used there with an efficiency of 1.0 it would provide the RDP for an ME intake of only about 10 MJ/d. Assuming the pasture eaten had M/D = 6 (i.e. 0.47 DMD), the steer would have to eat about 5.4 kg DM (32 MJ of ME) to satisfy $ME_m = (27–7)/0.62$, and there would have to be 50 g CP/kg DM with dg = 1.0 to meet the RDP need for this ME intake. In reality, dry-season pastures can have a DMD of less than 0.47 and a CP content of less than 50 g/kg DM of which only 0.7 may be degradable. This example illustrates the need for an appropriate N supplement if liveweight losses are to be reduced (see below), and the reasons why appropriate supplements are effective. Their first effect is to promote microbial activity in the rumen, and thence increase feed intake that provides the animal with an increased amount of ME.

In calorimetric studies on 14 dairy cows in early lactation, when they were producing 27–40 kg milk/d, Flatt (1966) found that although they were fed *ad libitum*, their energy balances were negative to the extent that body tissues were being catabolised at a rate that, on average,

provided more than 40 MJ/d of net energy. If it is assumed that 1 kg loss in W provided 25 MJ of net energy and empty body loss provided (25/0.92) MJ/kg, then with a 40 MJ negative energy balance the quantity of protein catabolised may be predicted with equation 1.28 from Garrett (1987) as 252 g/d. This could not have provided the cows with more than about 0.2 of the 1260 g RDP/d they would have needed for their mean ME intake of about 150 MJ/d from about 12 kg DM/d (Flatt *et al.* 1969). The 252 g/d body protein loss is thus equivalent to only 21 g of protein per kg DM of the feed eaten (M/D 12.5).

Non-lactating animals

It is recommended that no account be taken of contributions to RDP from protein catabolism during liveweight loss when assessing actual or required dietary protein intakes and the need for a supplement (see below). On the other hand, Revell *et al.* (1999) have shown that mobilised protein is used for wool synthesis to an extent that is limited only by the concentration of S-containing amino acids in the mobilised tissue.

Lactating animals

It is recommended that, as with animals not lactating, there should be no allowance for contributions from tissue proteins to RDP. Contributions that were made could have beneficial effects similar to those from increases in dietary CP concentrations reported by Oldham and Alderman (1982). They showed that with increases at least up to 180 g CP/kg DM there was increasing DMI by dairy cows, and that for each increment of 10 g CP/kg DM the OMD increased by 0.01 units. Increases in milk yields corresponded with the increases in ME intake.

Especially with high milk yields in early lactation, a loss in W appears to be inevitable. Because the amino acids from the catabolised tissues will be indistinguishable in the body from those of dietary origin, it is likely that they will be used in the synthesis of milk and will have much more significance in this process than for the RDP supply. Amino acids from the tissues are, in effect, truly absorbed. Consequently, it could be expected that they would be used for milk with greater efficiency than the efficiency of 0.7 assumed for DPLS; the value of 0.8, used by the ARC (1984) for truly absorbed amino acids, is **adopted** here. It can be noted that the slightly higher value of 0.84 has been assumed for the conversion of energy from body tissues to milk energy.

The quantity of tissue protein catabolised during liveweight loss may be estimated by means similar to those used to estimate body protein in weight gain in mature animals (equation 1.34 or 1.34A).

Estimates of requirements as DPLS and dietary CP concentrations

Pre-ruminant lambs and calves

In the absence of significant microbial activity and MCP synthesis in the rumen, the protein value of the liquid feed of lambs and calves, and their protein requirements, are defined in terms of the digestibility of the protein intake and the efficiency of use of the DPLS. There is negligible, if any, use of non-milk proteins such as from soyabean in Australian milk substitutes. These substitutes include whole milk, skim milk and buttermilk powders, and dried whey in amounts less than those likely to cause scouring in the animal. From information reviewed by the ARC (1980) and Roy (1980), the apparent digestibility of the proteins in whole milk and the milk by-products can be taken to be 0.92, and though there are some differences in amino acid

composition, the net efficiency of use of the DPLS for purposes other than wool growth can be taken to be 0.8 (cf. 0.7 for other animals). For wool an efficiency of 0.6, as for older sheep, is assumed.

These two efficiency values are used to convert the net protein requirements for growth and wool synthesis to estimated dietary requirements for DPLS and, thence, CP g/kg. The net protein requirements for urinary endogenous losses are calculated with equation 2.20 or 2.21 for respectively calves and lambs; those for body growth with equation 1.31; and those for wool growth with equation 2.27. Equation 2.23 is used to estimate the small dermal losses by calves.

Allowance is made for endogenous faecal losses but as, in the pre-ruminant, microbial N will make only a small contribution to faecal CP, an estimate of faecal loss more closely resembling that from non-ruminants is appropriate, rather than from equation 2.22. The studies of Walker and Cook (1967) and Hogan and Weston (1968) indicate 10.6 g EFP/kg DMI (i.e. 1.7 g N) but the slightly higher 1.9 g N (Roy 1980), that is 12 g EFP/kg DMI, is **adopted** here.

Ruminants

The examples in Tables 2.5 and 2.6 of the estimation of DPLS requirements, and the corresponding dietary concentrations of CP of specified degradability, are for the animals and diets used in Tables 1.14 and 1.15 to illustrate the estimation of ME requirements for maintenance and production. For housed animals, diets with M/D = 11 were chosen to facilitate comparisons between the estimates and those from other sources. As the estimates depend strongly on the effective degradability of dietary protein, these tables merely illustrate isolated examples of the sequence of calculations. A small spreadsheet computer program (CP Required) is freely available at www.pi.csiro.au/grazplan to make the appropriate computation for a particular feeding situation. The inputs for this program would normally be derived from the use of the GrazFeed decision support tool (see p. 233) or the program ME Required (see p. 52).

The estimates given should be regarded as the minimum amount of RDP to be supplied by diet CP and, if the resulting MCP is less than the DPLS requirement of the animal, as the minimum UDP supply. The requirements depend on the Edg selected for the diet. If, improbably, they could be achieved exactly in diet formulations then the CP would exactly provide the RDP requirement and the estimated amount of protein in addition to MCP needed by the animal that was to be supplied as UDP. With formulations for lower Edg, the dietary CP concentration has to be increased in order to provide the RDP required, but because of the associated increase in UDP supply the estimated protein requirement of the animal will be exceeded.

With higher Edg, the dietary CP again may have to be increased so that it will provide the necessary amount of UDP but in this instance there will be an excess of RDP. While Edg is a property of the feed rather than a requirement as such, it is shown in the following discussion that there are constraints on the range in Edg that is appropriate with practical diets for particular purposes. With a high-yielding dairy cow (Table 2.6) for example, formulations to provide the RDP and UDP required become increasingly impractical as Edg exceeds about 0.7 and it becomes less likely that high milk production would be achieved.

(*a*) *Growing steer* (*Table 2.5*). The 300 kg Hereford steer fed 7 kg DM/d of a mixed diet providing 77 MJ of ME in order to gain 1 kg W/d is estimated to require 406 g/day DPLS, a similar value to that estimated by AFRC (1993). From its ME intake the animal requires 630 g/day RDP for microbial synthesis. With Edg = 0.9, a diet containing 100 g/kg DM of CP would provide this

amount of RDP, leaving the remainder of the DPLS to come from the UDP. At Edg = 0.7, the required concentration would increase to 129 g CP/kg DM.

Table 2.5. Estimated net and dietary protein requirements of a 300 kg Hereford steer eating 7.0 kg dry matter per day (77 MJ ME) and gaining 1 kg live weight per day, and of a Dorset wether sheep eating 1.24 kg dry matter per day (13.6 MJ ME) and gaining 0.2 kg per day (see Table 1.14)

	Steer	Wether
Net protein requirement (g/d)		
EUP (equations 2.20 and 2.21)	49	7.8
EFP (equation 2.22)	107	18.8
Dermal loss (equation 2.23)	8	–
Wool	–	8.4
Protein in gain (equation 1.31)	120	23.0
TOTAL	284	58.0
Equivalent as DPLS (Total/0.7[A])	406	83
Estimates by AFRC (1993)	403	100
Dietary supplies (g/d)		
RDP required for MCP (FME x g MCP/MJ)	630	115
Microbial DPLS (MCP x 0.6)	378	69
Requirement for DUDP	28	14
UDP (= DUDP/0.7)[B]	40	20
Minimum CP requirement	670	135
Dietary CP required (g CP/kg DM)		
At Edg[C] = 0.9	100	110
At Edg = 0.8	113	116
At Edg = 0.7	129	132

[A] Divide by 0.6 for wool.
[B] For more accurate estimate of digestibility of UDP, see equations 2.18 and 2.19.
[C] Effective degradability of dietary protein.

(*b*) *Growing sheep* (*Table 2.5*). The estimated net protein requirement of 58 g/d of the wether gaining 0.2 kg/d, is similar to the estimate of 61 g/d from Black and Griffiths (1975), based on their predicted requirement for a 30 kg lamb of about (0.8 × 6.25) g net protein per MJ of ME and an ME intake of 12.2 MJ/d. However, the estimated DPLS requirement is lower than that of AFRC (1993).

The estimated dietary protein requirement increases from 110 to 132 CP/kg DM as Edg falls from 0.9 to 0.7, in order to maintain the supply of RDP for microbial synthesis.

(*c*) *Dairy cow* (*Table 2.6*). The estimated requirement of 160 g CP/kg DM (Edg = 0.7) for a 600 kg cow producing 30 kg milk/d is similar to the 176 g CP/kg DM (Edg = 0.56) of the NRC (1989) that makes small allowances for foetal growth (at 150 d pregnant) and liveweight gain (0.1 kg/d). Such allowances should be included when appropriate; they will generally be small until the cows are in the later stages of gestation and should be making gains in W to restore earlier loss. A liveweight loss can be expected in early lactation when an allowance is to be made for the use for milk protein synthesis, with 0.8 efficiency of amino acids from catabolised tissues (see p. 98). The present estimates substantially exceed the earlier estimates of ARC (1980, 1984) of about 120 g CP/kg DM (Edg = 0.76).

Table 2.6. Estimated net and dietary protein requirements of a 600 kg lactating Friesian cow eating 19.3 kg dry matter per day (212 MJ ME) and yielding 30 kg milk per day, and of a 50 kg lactating Merino ewe eating 1.73 kg dry matter per day (21.5 MJ ME) and yielding 1.5 kg milk/d (see Table 1.15)

	Cow	Ewe
Net protein requirement (g/d)		
EUP (equation 2.20)	61	10.7
EFP (equation 2.22)	293	26.3
Dermal loss (equation 2.23)	13	–
Wool	–	11.0
Milk[A]	969	67.5
TOTAL	1336	116
Equivalent as DPLS (Total/0.7[B])	1909	160
Dietary supplies (g/d)		
RDP required for MCP (FME x g MCP/MJ)	2100	213
Microbial DPLS (MCP x 0.6)	1260	128
Requirement for: DUDP	649	32
UDP (= DUDP/0.7[C])	927	46
Dietary CP required (g CP/kg DM)		
At Edg = 0.8	240	154
At Edg = 0.7	160	176
At Edg = 0.6	181	205
Other estimates: AFRC (1993)[D]	167	160
NRC (1989)[E]	176	–

[A] Cow: 32.3 g protein/kg; Ewe: 45 g protein/kg.
[B] Divide by 0.6, rather than 0.7, for wool.
[C] For more accurate estimate of digestibility of UDP, see equations 2.18 and 2.19.
[D] Edg not stated.
[E] At Edg = 0.56.

The predicted requirements for values of Edg other than 0.7 demonstrate the high sensitivity of estimates to this variable. With the values used in Table 2.6, UDP is the limiting factor when Edg = 0.8 but RDP sets the limit when Edg = 0.6. A degradability as high as 0.75 would generally be unattainable in a ration for a housed dairy cow; an appropriate ration would usually contain substantial amounts of cereal and protein supplements for which most tabulated degradability values at high levels of intake are less than 0.70.

On herbage diets Edg is often higher, the digestibility of UDP is often higher (see equation 2.18) and the potential for MCP synthesis is higher, at least in the spring (see equation 2.16). If the same calculations shown in Table 2.6 are applied to the values indicated for a grazing cow in Table 1.15, the estimates of RDP and UDP requirements for spring grazing are 2421 g and 585 g, respectively. For Edg = 0.8, these needs would be met by a diet containing 152 g CP/kg and for Edg = 0.7 the need would increase to 173 g/kg, in each case the limit being set by the high potential for MCP synthesis. On autumn pasture, where this potential is lower, the estimated needs for RDP and UDP are 2044 g and 867 g, respectively. For Edg = 0.8, these needs would be met by a diet containing 218 g CP/kg, UDP setting the limit, whereas at Edg = 0.7, a diet containing 147 g CP/kg would meet both RDP and UDP requirements. This variability in the estimated need for additional UDP by grazing cows is borne out by the equivocal nature of responses to supplements of formaldehyde-treated casein (e.g. Rogers *et al.* 1980; Minson 1981*a*).

Practical rations based on silage are exemplified by those used in the experiments of Mayne and Gordon (1984) and Gordon and Peoples (1986) with Friesian cows and heifers (first lactation). Grass silage (Edg = 0.82) provided about 60% of the DMI of the cows during the first 14 weeks approximately of lactation when mean milk yield was about 25 kg/d, and about 53% of DMI by the heifers during the first 20 weeks approximately of lactation when mean milk yield was about 21 kg/d. The Edg of the additional protein supplied in the other part of the rations varied from 0.39–0.62. The whole rations contained from 152–196 g CP/kg DM with a mean Edg, calculated from the published estimates of RDP and UDP supplies, of 0.68. Gordon and Peoples (1986) stated that the response in milk yield to increased CP intake they observed, 0.18 kg/d per 100 g CPI/d, was within the range of responses of 0.08–0.40 kg milk/d observed in numerous other studies. Information on changes in W and CS was given in some of these (e.g. Gordon and McMurray 1979) that indicated catabolism of body tissues was occurring.

Tissue catabolism usually occurs for some time after parturition (see p. 40) when the rate of increase in voluntary food intake (Chapter 6) lags behind the increase in requirement following the onset of lactation. The extent of this catabolism is masked to varying degrees by changes in body water. Substantial use of body tissues could be expected for a milk yield of 30 kg/d. The estimated CP requirements are reduced if allowance is made for protein contributions from body tissues (see p. 98).

Despite the equivocal nature of these responses, supplementary UDP (e.g. formaldehyde-treated casein, FC) with pastures similar in quality to those used in these studies, could confer specific nutritional (but not necessarily economic) benefits. Pasture intake might be increased (Stobbs *et al.* 1977) or not reduced (Flores *et al.* 1979) so that UDP was a true supplement. The milk yield response to UDP will obviously vary with pasture CP content. The expectation that it would increase with level of production (increasing milk protein output) has been confirmed by Rogers *et al.* (1980) who found that for each 1 kg/d increment in milk yield, the response to 1 kg FC/d increased by 0.5 kg milk/d.

(*d*) *Lactating Merino ewe* (*Table 2.6*). The housed ewe with an ME intake of 19.1 MJ/d from 1.73 kg DM/d, yielding 1.5 kg milk/d, is estimated to require 176 g CP/kg DM with Edg = 0.7. It is not possible to compare this usefully with other estimates for which Edg values are not available. It is clear from the estimates at different Edg that, for the lactating ewe, a shortage of RDP as Edg decreases is more likely to be limiting than a shortage of UDP as Edg increases. However, in twin-bearing ewes there would be more need for UDP and some reports indicate substantial responses by lactating ewes of other breeds to increasing supplies of CP with low degradability, e.g. Gonzalez *et al.* (1982).

With the 50 kg lactating Merino ewe at pasture, eating 1.95 kg DM/d with a DMD of 0.77 (Table 1.15), and with a predicted clean wool production of 12 g/d (equation 2.27), the estimates of CP requirements are reasonably consistent with CP contents observed in the types of pastures they would graze. On a temperate spring pasture, the estimates for RDP and UDP requirements of 229 g and 23 g/d, respectively would be met by a diet containing 157 g CP/kg DM with Edg = 0.75. With autumn pasture, the estimated needs for RDP and UDP of 193 g and 47 g, respectively, would be met by a diet containing 132 g CP/kg DM with Edg = 0.75.

Guidelines for the use of protein or NPN supplements

A protein supplement, but not NPN, will supply some ME, but responses by animals to either type of supplement will be determined primarily by the extent to which they gain additional ME from an increase in forage intake, if forage availability is sufficient to allow this, and from an increase in its digestibility. With sheep, even small quantities of green material among a large mass of dry standing material can result in a CP intake that is adequate in relation to their DM (i.e. ME) intake. Cattle, however, are less able to select the green material from such pastures and so their intake will have lower CP content and digestibility than the diet selected by sheep. They are, therefore, more likely to respond to NPN or protein supplements under similar conditions (Langlands and Bowles 1976; Langlands and Sanson 1976).

When an inadequate CP intake is identified, there are two considerations in assessing the type of supplement that is appropriate. The first is the requirement of the rumen microbial population for simple forms of N, and the second is the need to enhance protein flow to the intestines by providing UDP.

Rumen microbial population

The microbial population requires simple forms of N, principally as ammonia, for protein synthesis and growth. Concentrations in ruminal fluid of not less than 60 to 80 mg ammonia N/l are necessary (Pisulewski *et al.* 1981), and increases in feed intake have been observed with higher concentrations (Boniface *et al.* 1986); as much as 235 mg ammonia N/1 (Mehrez *et al.* 1977) may be required for maximal rate of fermentation. The diet should also provide 0.07 g S (cattle) or 0.08 g S (sheep) per g N from RDP (see p. 163). Other minerals may also be required. With cattle, additional P may be necessary because of the low plant P contents that are common in Australia. Observed responses by grazing cattle following applications of superphosphate fertiliser to the pasture as well as to direct supplementation with P (Coates 1987) may stem from effects on ruminal fermentation as well as upon the animals themselves. It has been reported that microbial protein synthesis was maximised with diets containing 5.1 g P/kg DOM (Breves and Hoeller 1987; Komisarczuk *et al.* 1987), but the required concentration would presumably vary with the rumen availability of the P.

Indicators of inadequate CP intake

A dietary N content of around 1%, say 70 g CP/kg DM, has for a long time been regarded as a minimum, at which there is a risk of impaired ruminal fermentation and below which there will increasingly be reductions in feed intake and animal performance. More recent knowledge of protein nutrition does provide some support for this criterion. Suppose M/D = 6 for a forage, then (Table 2.5) the RDP requirement would be $(8.4 \times 6) = 50.4$ g/kg DM that would be provided by 70 g CP/kg DM if 0.72 of the CP was degraded. However, a lower dg is more likely, and even if it were 0.72 the N would have to become available from RDP at a rate that matched the contemporary requirements of the microbial population, with additional RDP to allow for that absorbed and removed in digesta outflow from the rumen. Thus, although recycling of N to the rumen (see p. 97) could offset some inadequacy, a 'critical' minimum CP content in a feed is not a reliable guide without information on the rate and extent of degradation of the CP and on ammonia removal.

In studies with cattle grazing speargrass (*Heteropogon*) / kangaroo grass (*Themeda*) pastures near Townsville, Queensland, Winks and Laing (1972) obtained no responses to a supplement of urea plus molasses and P until faecal CP concentration fell below 80 g/kg DM. As with the feed CP content, the crucial test of whether a given value is a reliable indicator of inadequate CP intake is the extent to which it represents an inadequacy in ruminally available N. With both cattle (D. W. Hennessy pers. comm.) and sheep (R. M. Dixon pers. comm.) no significant or consistent relationships were found between rumen ammonia and faecal N concentrations. Consequently, unless relationships can be established that are specific for forage type, amount eaten, and type and breed of animal, faecal CP will not be a reliable guide to a need for N supplementation.

In a more functional approach to the assessment of the protein adequacy of forages, Hogan (1982) suggested that N limitation to microbial protein synthesis is likely if the ratio (g/g) of DOM to CP exceeds 10:1. Reference to DOM makes some indirect allowance for variation in dg. As tropical forages mature the ratio approaches, and can exceed, 20:1, whereas the ratio in improved pastures in southern Australia is often 5:1 or narrower. With a 10:1 ratio, Hogan (1982) suggests animal production will tend to be limited by the intake of ME rather than of CP, though for lamb growth about 6:1 appears to be optimal (Faichney and Weston 1971; Weston 1971).

The most direct measure of the adequacy of N for microbial fermentation and growth is the ammonia concentration in ruminal fluid. McMeniman (1981) has developed a method, for use by advisory officers in Queensland, for sampling ruminal fluid by stomach tube, and assessing the ammonia concentration by comparing the colour developed upon addition of reagents with that developed in standard ammonia solutions. Alternatively, blood can be sampled from the caudal (tail) or jugular vein to determine the plasma urea N concentration, which is closely related to rumen ammonia concentration in both sheep (Weston and Hogan 1968) and cattle (Hennessy and Nolan 1988).

NPN supplements

It is desirable that an NPN supplement should achieve a persistent increase in rumen ammonia concentration. Urea is rapidly hydrolysed in the rumen by bacterial urease, and if there is only an intermittent intake its effect will be transient; indeed it may result in ammonia toxicity if a large amount is consumed. Other forms of NPN have been tested. Ammonium salts, such as the phosphates, do not appear to be any more beneficial (Leng *et al.* 1973). Two other compounds that yield ammonia more slowly and are therefore less likely to lead to intoxication, are biuret and isobutylidene diurea (IBDU). Meggison *et al.* (1979) assessed their value for cattle from the increase in MCP flow to the duodenum above that observed when no NPN was added to the diet. The transient effect of an intermittent intake of urea (twice or three times per day) was illustrated by a recovery in MCP of, at most, only 0.17 of its N. With a near-continuous urea intake, the recovery was 0.79. This value is similar to the efficiency of 0.8 for the use of NPN assumed by the ARC (1984).

In the same study, observations with biuret and IBDU given twice or three times daily gave efficiencies of N use ranging from zero to 0.9. Lindsay *et al.* (1984), included urea or IBDU in a hay diet (25 g CP/kg DM) given once daily to steers and observed no response that could be attributed to a slower release of N from the IBDU. This form of NPN is considerably more expensive than urea, as is biuret. A problem with biuret (Leng *et al.* 1973) is that up to six weeks is needed after its inclusion in the diet before the rumen microbial population produces effective

amounts of biuretase. During this period a significant fraction of the biuret is absorbed as such, excreted in the urine, and thus wasted. Even after microbial adaptation, such wastage can still occur and it may have phytotoxic effects (Reeves *et al.* 1977).

Reported responses to urea tend to be greater with housed animals, when it has been mixed with their feed, than with grazing animals for reasons already given. In general, the benefits of NPN supplementation are reduced liveweight loss and improved survival of animals on poor pasture, compared with their unsupplemented counterparts, rather than weight gains or even maintenance of W (e.g. Nolan *et al.* 1974). A lower loss in W of animals given urea during the dry season may subsequently be reflected in a persistently higher W than for animals that had not been given the supplement (e.g. Winks and Laing 1972; Winks *et al.* 1972; Hennessy *et al.* 1981), although compensatory gains made when good feed becomes available can reduce or sometimes even eliminate the differences (Allden 1982).

A common and effective method of providing urea is to mix it with molasses, the mixture being placed in 'drum lickers'—a roller drum floating on top of the mixture. The molasses provides readily fermentable carbohydrate for the rumen microbes and supplies their need for S; with cattle it may be advisable to include a P supplement. Techniques used and experiences with this 'fortified molasses' (FM) are described by Wythes and Ernst (1984). The addition of 30 g urea/kg molasses is appropriate if FM has to be the major part of the animals' diet because little or no other feed is available. A mixture of 80 g urea/kg molasses is consumed in smaller amounts, and may be less acceptable to *B. taurus* than *B. indicus* breeds; it has been found to supply animals with suitable amounts of N and, compared with 30 g urea/kg FM, results in less expenditure on purchase, mixing and distribution. Daily intakes vary with pasture availability but are about 2 kg by adult cattle and 1 kg by weaners, thus providing about 70 and 35 g urea N/d respectively. The urea must be well mixed into the molasses to minimise risk of urea toxicity, which can also arise if rainwater dissolves urea from, and lies on top of, the FM. The concentration of urea in the mix should be gradually increased over a fortnight to enable animals to adjust to the supplement.

A more costly method of providing urea is in the form of blocks of various formulations (e.g. Miller 1998), often including molasses and salt. A problem with these blocks is that many animals in a flock or herd will not lick them at all or to only a small extent, while others will consume large amounts (Lobato and Pearce 1980).

Controlled addition of urea to drinking water from a dispenser in the supply line to a trough (Stephenson and Hopkins 1985, Miller 1998) may be an effective method of supplementation provided there is no other source of water (e.g. dams), and climatic conditions promote drinking (see Chapter 5). Dispensers available commercially generally deliver urea at rates of 1.6–2.9 g/l of water (e.g. Stephenson *et al.* 1981) and so sheep drinking 5 l water/d will consume 3.7–6.8 g urea N/d.

Protein supplements

While NPN supplements alone may do no more than maintain W, more positive effects may be desirable, particularly with some classes of livestock. Examples are pregnant and lactating females during drought and their young weaned at an early age in these conditions (Wythes and Ernst 1984; Hennessy 1986). Strategic supplementation for liveweight gain by young heifers can bring them to a size suitable for mating at 15 months of age whereas with no supplement they may not breed for another year or more (Hennessy and Williamson 1988).

The RDP in protein meals provides N compounds, including peptides, which can enhance microbial activity (Thomsen 1985). The UDP directly increases the supply of DPLS (amino acids) to the animal, and in addition to the immediate benefits there is evidence (Egan 1965) for a systemic effect in the animal that results in an increased intake of protein-poor feed. For these effects the quantity of protein meal required is small, about 0.5 kg/d for cattle grazing low-quality pasture and pro rata with W for sheep. Larger amounts may of course be provided when responses, allowing for the substitution effect (Chapter 6), can be predicted with the information given in Chapters 1 and 2. The effectiveness of even small additions to the supply of amino acids is illustrated by the experiment of Lindsay *et al.* (1988) with steers (160 kg W) given a hay containing 25 g CP/kg DM plus 30 g urea N/d. With 125 g/d of formaldehyde-treated protein meal their liveweight gain was 40 g/d, and was increased to 120 g/d by the addition of 12 g/d methionine plus 6 g/d lysine, both protected from ruminal degradation. Gains were not significantly greater when the supplement was 250 or 400 g/d of the protein meal with, or without, the protected amino acids.

Oddy and Sainz (2002) concluded that if energy intake is adequate for growth in weaned lambs and the intake of RDP is sufficient for MCP production, then the response to additional (protected) amino acid supply is variable. On the other hand, if energy intake is at maintenance level or below, an increase in post-ruminal amino acid supply may stimulate liveweight gain, albeit at low levels (Dove 2003). As indicated on p. 95, wool growth is a process that, under many conditions, may respond to supplementation with protected sulfur-rich amino acids.

In situations where a response can be expected, protein feeds with low dg should be selected; such as cottonseed meal, or those that have had their ruminal degradability reduced by chemical (e.g. formaldehyde) or physical (e.g. heating) treatments. Treatment involves additional expense and it should be borne in mind that as most of these meals will have dg of at least 0.5, some of the claimed benefits from their use may result from RDP released slowly into the rumen, rather than from the protected protein (O'Reagain and McMeniman 2002).

Whole cottonseeds and lupins can be fed on the ground while protein meals should be fed in troughs to avoid severe wastage and soil ingestion. Pelleting reduces wastage from troughs (Dove and Freer 1986); with cattle at least 300 mm lineal space per animal should be allowed when frequent or small offerings are made. A number of troughs, separated by 2–3 m is desirable to reduce behavioural effects that reduce the intake by some animals (see p. 229). The meals may be mixed with molasses to improve palatability (Wythes and Ernst 1984).

Appendix 2A

Recommended procedures for the estimation of the degradability of feed proteins by the artificial fibre bag (*in sacco*) method

These recommendations (apart from some comments in the concluding Note) are those proposed and adopted by AFRC (1992) to provide a standard method for measuring degradability parameters that can be used to estimate the effective degradability of protein in feeds.

(a) Bag specifications

Materials. Synthetic polyester fibre

Pore size. 40–50 μm

Open area. Approximately 26%

Dimensions. 10 cm × 21 cm with a round base

Stitching. French seams and a small stitch should be used (2-ply 50 denier polyester thread, 10/70 ball-point needle, lockstitch, approximately 10 stitches per cm). Where practically possible, the seams should be sealed using a silicone-based sealant to prevent the loss of material through the stitch holes. Where sealing is not routinely practised, the bags should be checked after each use and, if holes are seen, a sealant should be used.

Fastening. No recommendation is made but it is essential to ensure a tight seal is made.

Durability. Regular inspection of bags should be made to discard those damaged by puncturing. Alternatively, these should be repaired using a silicone-based sealant. A random selection should be made to eliminate any bias that may be due to age of the bag.

(b) Sample preparation

Concentrates. Air-dried samples to be milled through a 2.5 mm screen with fine particles removed by sieving across a 45 μm sieve. Cubed or pelleted compound feeds may be crushed, but this should be done to achieve a particle size similar to that obtained with milled samples. High-oil seeds or similar feeds difficult to handle may be ground up with dry ice. In all cases, if more than 5% of any sample passes through a 45 μm sieve, an alternative method such as cracking should be employed.

Forages and succulents. Air-dried forages to be milled through a 4 mm screen and sieved (as for concentrates). Grass and silage to be chopped by hand to approximately 1 cm length (either in fresh or frozen state). In all procedures, care must be taken to avoid losses of juice.

Sample size. Approximately 5 g DM per bag, irrespective of feed type.

(c) Animals and feeding

Species. No recommendations can be made, bearing in mind the limitations of facilities, cost etc. Cattle, however, offer the option of greater throughput of samples and replication. The type of animal should be stated when results are reported.

Feeding. Animals should receive a maintenance level of feeding and a 60:40 (DM basis) forage/pelleted concentrate diet is recommended. Specifications for the concentrate may vary but it should provide approximately 17.5% crude protein, 5–8% fibre, 4–4.5% oil and 23–28% starch. Forage should consist of average/good quality grass hay, dried grass or silage. Feed should

be offered in a minimum of four feeds daily, spread as evenly as possible over 24 hours.

It is recognised that for highly productive stock (e.g. lactating dairy cows) a 50:50 forage/concentrate diet may be more appropriate. Changes in forage/concentrate ratios and level of feeding may also influence the pattern of N disappearance from polyester bags. Any deviation, therefore, from the above recommendation should be clearly stated.

Where bag changes coincide with feeding times, it is recommended that they be incubated or removed before feeding.

(d) Incubation procedure

Placement. Bags should either be attached on semi-rigid stalks or sufficiently weighted (e.g. 1 kg for a dairy cow) to ensure immediate insertion within the liquid of the rumen contents but allowing free movement.

Incubation. Zero-hour estimates of degradability should be obtained by submitting duplicate bags containing sample material to the washing procedure described below. Remaining bags should be placed directly in the rumen without prior wetting. Times of withdrawal of incubated bags should be selected to ensure optimum definition of the critical point of degradability and it is recommended that forages and concentrates be taken to a maximum of 72 and 48 hours, respectively. Thus incubation times for forages might be 8, 12, 24, 48 and 72 hours and for concentrates, 2, 6, 8, 24 and 48 hours.

Either a sequential withdrawal method or a complete exchange method for insertion and removal of bags may be used (see Paine *et al.* 1982 for details).

Replication. It is recommended there should be a minimum of three animals × 1 bag per incubation time (estimated SEM = 1.5%). Increased precision would be obtained by increasing the number of animals per incubation time.

(e) Sample processing post incubation

On removal, the bags should be washed in a washing machine set for a 50–60 minute (cold water) wash cycle, followed by slow (500–600 rpm) spin. Where mechanical washing is unavailable, bags should be gently washed by hand under running water until the rinse water is clean. Bags may be stored frozen following a pre-wash until sufficient bags have been collected for batch washing. Whichever method is used, it is recommended that standard samples are washed periodically to check for variations and errors in sample processing.

Bags and residues should be frozen immediately and stored frozen (–20°C) until freeze-dried. On drying, the bags should be stored in a desiccator over phosphorus pentoxide or orange silica gel until weighed. After weighing, samples should be ground to ensure homogeneity and analysed for nitrogen concentration.

(f) Results

Results should be expressed as the loss of nitrogen from the bag at the time (t) of incubation.

$$\text{N loss} = 1 - (\text{Residual N in bag})/(\text{Original N in bag at } t = 0)$$

Note:

(*1*) Practical limitations may necessitate modifications to the above method. It is important that these are recorded and reported. For example, freeze-drying may provide a more practicable solution to the problems of testing fresh herbage in the wet state. Wales

et al. (1999) have reported the use of this procedure and their deviations from the general recommendations.

In addition, it is recommended that simple rumen parameters (% ammonia and pH) be monitored regularly as markers of rumen stability.

(*2*) The procedure described above is appropriate for concentrate feeds but the simple analysis for nitrogen remaining in the bags (*e* and *f* above) is not satisfactory for most forage samples, e.g. hay, silage. Nor is it suitable for fresh herbage or extrusa from grazed pasture with IVDMD <70%, because of microbial contamination of the sample during incubation. For this material, it is essential that the procedure be used to measure the rate of disappearance of neutral detergent insoluble protein (NDIN × 6.25), rather than N (see text).

Appendix 2B

Main equations for predicting protein requirements

Refer to the main text for the definitions of variables.

Net protein requirement (g/d) — Equation no.

Maintenance, P_m (P_m = EUP + EFP + DPL)

Endogenous urinary protein, EUP

Cattle

$$EUP = 16.1 \ln W - 42.2 \quad (2.20)$$

Sheep

$$EUP = 0.147\ W + 3.375 \quad (2.21)$$

Endogenous faecal protein, EFP

$$EFP = 15.2\ DMI \quad (DMI \text{ in kg}) \quad (2.22)$$

Dermal protein loss, DPL (cattle only)

$$DPL = 0.11\ W^{0.75} \quad (2.23)$$

Wool growth, P_w (sheep)

$$P_w = \frac{SFW}{SRW} AF \cdot DLF \min(1.16 DPLS_w, 14 ME_w) \quad (2.27)$$

Gestation, P_c

Protein content (Y, kg) of foetus(es) or gravid uterus, using appropriate values of A, B and C from Gestation section, for n young. SBW = expected birth weight/4 kg (lamb) or 40 kg (calf)

$$Y = n\, SBW \exp(A - B\exp(-Ct)) \quad (2.24)$$

Protein gain during gestation (g/d)

$$P_c = 1000 \cdot n\, B\, C \exp(-Ct) Y \quad (1.26)$$

Weight gain (the same equations apply to loss), P_g

(a) Immature animals

Protein in liveweight gain, PV (g/kg)

$$PV = 0.92((212 - 4R) - (a - 4R)/(1 + \exp(-6(Z - 0.4)))) \quad (1.31)$$

a = 120 for large, lean cattle; 140 otherwise

R = (MEI / ME_m) – 2

Z = W / SRW; max. value = 1.0

(b) Mature animals

$$PV = 0.92(187 - 115 W / SRW) \quad (1.34)$$

For large lean cattle, use 207 instead of 187

$$P_g = PV.\ LWG$$

Milk production, P_l

Protein content of milk (g/kg)

Cows and goats: *MP* = 32 (or use equations 2.26 A–D for cow breeds)

Sheep: *MP* = 45

$P_l = MP.\ Milk$

Total net protein requirement

$$P_t = P_m + P_w + P_c + P_g + P_l$$

$$\text{Equivalent as DPLS} = (P_m + P_c + P_g + P_l) / 0.7 + P_w / 0.6 = DPLS_t$$

Dietary supply (g/d)

Supply of microbial protein and requirement for RDP

General equation

$$MCP = FME(7 + 6(1 - e^{-0.35L})) \tag{2.15}$$

Alternative equation for temperate pastures

$$MCP = FME(7 + 5(1 - e^{-0.35L}))(1.0 + 0.1(\lambda \sin(0.0172T) / 40)) \tag{2.16}$$

Alternative equation for tropical pastures

$$MCP = FME(6 + 6(1 - e^{-0.35L})) \tag{2.17}$$

FME (MJ) = MEI – Energy of (fat + UDP + silage acids)

$RDP_{required} = MCP$

$DPLS_{mcp} = 0.6\ MCP$

Requirement for UDP

Requirement for digestible UDP

$$DPLS_{udp} = max(0, DPLS_t - DPLS_{mcp})$$

True digestibility of UDP

Forages $$DUDP / UDP = 0.0055CP - 0.178 \tag{2.18}$$

Concentrate feeds $$DUDP / UDP = 0.9(1 - (ADIP / UDP)) \tag{2.19}$$

$UDP_{required} = DPLS_{udp}\ (UDP/DUDP)$

Minimum CP requirement is $RDP_{required} + UDP_{required}$

Dietary CP required (g CP/kg DM) at different levels of effective degradation

$$CP_{required} = \max((RDP_{required} / Edg), (UDP_{required} / (1 - Edg))) / DMI$$

Chapter 3

Minerals

Summary

The 14 minerals considered as essential nutrients range from the macromineral P that has a wide range of vital functions in the body to the micromineral I that has just one. In addition, there are a few apparently non-essential minerals that may depress productivity when in excess. Gross deficiencies of essential minerals become evident from a variety of clinical signs, as do excesses, but the major problem in practice is generally the recognition of subclinical deficiencies. These are frequently transient and may reduce animal production with few specific signs. The realisation of a mineral deficiency may be delayed by the ability of the animal to utilise body reserves (e.g. Ca) or stored excesses (e.g. Cu), often for periods of weeks or months. In a number of instances the dietary mineral concentration that would be adequate is not closely defined and cannot be predicted reliably from analysis of the feed.

A major uncertainty in assessing requirement is the availability of a mineral to the animal. The proportion of the intake of a mineral that is absorbed and metabolised can vary with the age and physiological state of the animal, with the chemical form, and with the presence of other minerals and nutrients in the feed. For example, Cu nutrition is affected by Mo, S and Fe; Mg absorption is affected by K, by Na and by ruminal ammonia; and I and S requirements are affected by the presence of, respectively, goitrogenic and cyanogenic substances in the blood. Assessment of the net maintenance requirement for a mineral from the endogenous losses in faeces and urine can be unreliable because of variation in these losses with intake.

For such reasons, the following dietary mineral concentrations should be taken only as a guide to those that are desirable. When a range is given, the higher values are for rapidly growing, pregnant, or lactating animals, and the lower values are for those at maintenance or with a low level of production.

Mineral	Sheep	Cattle
	g/kg DM	
Calcium	1.4–7.0	2.0–11.0
Phosphorus	0.9–3.0	1.0–3.8
Chlorine	0.3–1.0	0.7–2.4
Magnesium	0.9–1.2	1.3–2.2
Potassium	5.0	5.0
Sodium	0.7–1.0	0.8–1.2
Sulfur	2.0	1.5

Mineral	Sheep	Cattle
	mg/kg DM	
Cobalt	0.08–0.15	0.07–0.15
Copper	4–14	4–14
Iodine	0.5	0.5
Iron	40	40
Manganese	20–25	20–25
Selenium	0.05	0.04
Zinc	9–20	9–20

Chlorine and K concentrations in most feeds are usually greater than those tabulated, and deficiencies are improbable. Sulfur requirements are better expressed as 0.08 g (sheep) or 0.07 g (cattle) per 6.25 g RDP (i.e. 1 g N; Chapter 2). Concentrations, per kg feed DM, of S exceeding 3 g, Mo exceeding 2 mg, Fe exceeding 500 mg, Zn exceeding 100 mg, or Cd exceeding 5 mg, can have adverse effects on Cu nutrition. Cadmium concentration should be less than 5 mg/kg DM to minimise the risk of its accumulation in liver and kidney to concentrations unacceptable in human food. For the same reason, Pb concentrations should be much less than 60 mg/kg DM, which is approximately the lower limit for toxicity in animals. Fluorine concentrations occurring naturally in feed plus water intakes should not exceed the equivalent of 35 mg F/kg DM; acute fluorosis can occur in animals grazing moist pasture with adherent superphosphate following recent application.

Introduction

The requirements for minerals, as for energy and protein, may be estimated factorially and then confirmed by reference to complementary feeding experiments both in the laboratory and the field. However, this procedure is difficult with some trace elements and the technique used involves monitoring the concentration of mineral in the feed over a wide range of long-term feeding experiments. A median value or a range between the concentration of mineral causing a chronic subclinical deficiency and that causing a chronic subclinical excess is, in most cases, identified as being the requirement. An exception to this general approach is Co, which is required in small amounts but is tolerated at very high levels without toxicity.

There are four factors that determine the amount of a mineral that passes to the tissues of the animal: (*a*) the concentration of the mineral in the feed, as affected by its availability from the soil and plant species and maturity; (*b*) the role of selective grazing in determining the proportions of different plant parts in the diet; (*c*) the availability of the mineral in the feed to the animal, as determined by the chemical form of the mineral and interactions with other components of the feed; and (*d*) the proportion of the mineral actually absorbed, as affected by the age, physiological requirement and nutritional history of the animal.

The net requirement for a mineral estimated by the factorial method is the sum of the quantities inevitably lost from the body as the endogenous excretions in faeces (FEL) and urine (UEL), for some minerals through the skin (S), and the quantities stored or secreted during growth of the body (G) and fleece (F), during pregnancy (P), and during lactation (L). The dietary requirement is taken to be the total net requirement divided by the coefficient of absorption on the assumption, at present unavoidable, of a uniform efficiency of use of the absorbed mineral for

all purposes. True absorption (TA) is the proportion of the dietary supply that enters the body from the gastro-intestinal tract, and when this is measured:

$$\text{Dietary requirement} = (\text{FEL} + \text{UEL} + \text{S} + \text{G} + \text{F} + \text{P} + \text{L})/\text{TA}$$

It should be noted that the factorial method does not make direct allowance for the requirements of the microbial population in the gut, particularly in the reticulo-rumen (e.g. for S) or for direct effects of a deficiency on voluntary intake of feed (e.g. for P) and so the estimated requirements tend to be minimal values. Numerous interactions in the gut (e.g. Cu-Mo-S) affect the availability of the mineral to the animal, and these may or may not be allowed for in defining TA. Both TA and the endogenous losses in faeces and urine may vary with mineral intakes above requirements (Suttle 1983*a*).

Determinations of clinical and subclinical deficiencies (or excesses) are ideally made from the levels of the nutrients in the metabolically active or major reserve sites in the body (e.g. Ca in cortical bone). More uncertain deficiency determinations can be made by measuring total daily mineral intake or the quantities in other animal tissues (including blood), faeces and urine, in plant tissues and finally in soils. As most of the animal measurements are invasive and difficult, dietary concentrations are commonly used as an indicator of mineral adequacy.

A deficiency or excess of a mineral in an animal occurs first in a subclinical rather than a clinical form. Further, mineral deficiencies rarely occur singly, are chronic rather than acute, and interactions with other nutrients commonly confound a diagnosis (for example Cu-Mo-S and P-N). Even when they are severe, there are rarely diagnostically specific signs and alternate diagnostic procedures need to be employed. An exception is the acute deficiencies of Ca and Mg that result in the severe neuro-muscular diseases hypocalcaemia (milk fever) and hypomagnesaemia (tetany), respectively. In the case of Ca, the trigger is a sudden and large increase in the animal's requirement for calcium at the start of lactation. In the case of Mg, the trigger is commonly a low Mg level in forages coupled with very lush feed that has a high gut transit rate and low absorption.

Requirements of all nutrients are estimated without reference to any clinical disease process, including parasitism. Many diseases result in a reduction in food intake or absorption of nutrients in the gastrointestinal tract or a loss of nutrients via the gastrointestinal tract. These may cause negative balances of nutrients and exacerbate the primary clinical condition. A simple example is diarrhoea in young calves where there is a gross negative balance for water and a whole range of minerals. In these conditions the primary disease condition needs to be corrected and the return to normality may be enhanced by supplying greater-than-normal quantities of nutrients.

Due to these uncertainties in factorial estimates, reference must also be made to the results of feeding experiments in which the mineral being studied is given to animals in two or more amounts and measurements are made of their performance (e.g. growth, concentrations of the mineral in body fluids and tissues, and physiological states and processes affected by an inadequacy). Substantial quantities of minerals can be stored in the body, particularly in bone and liver, and may be used to sustain the animal through longer periods of dietary inadequacy than can its reserves of energy, protein and water. The concentration of a mineral in a tissue (e.g. Cu in liver) may even increase during a period of liveweight loss. The duration of feeding experiments should therefore be sufficient to allow unbuffered expression of the effects of variation in dietary intake.

Several of the mineral elements required by the animal (Co, Cu, Fe, I, Mn, Se, Zn) are described as 'trace elements' essentially because they are required in quantities of mg/d, rather than g/d as with the 'major' minerals (Ca, P, Cl, K, Mg, Na, S). A few other elements are important either because of the risk of toxicity (Cd, F, Pb) or because of their interactions with the availability of essential elements (Mo interactions with Cu). For an authoritative review of mineral nutrition see Underwood and Suttle (1999) and for a review of issues in trace element nutrition see Lee *et al.* (1999).

In the absence of substantial scientific reports on the mineral requirements of goats, recommendations are based largely on those for cattle and sheep (AFRC 1998).

Calcium and phosphorus

Calcium and P are the two most plentiful minerals in the mammalian body, being the two dominant minerals in the hydroxyapatite crystal of bone and teeth. As 0.99 of the Ca and 0.80 of the P is in these tissues, it is customary to consider the two elements together. However, the other 0.20 of the P in the body is increasingly demanding separate attention. This fraction is involved in a wide range of intracellular energy and protein activities, including high-energy bonding in such molecules as adenosine triphosphate and creatine phosphate, as well as the structural integrity of cell walls as phospholipids. In addition, P is in DNA and RNA, and involved in the regulation of acid-base balance. Thus, it is vital to the normal functioning of every cell of the body, and to every microbe in the gastrointestinal tract.

Only small quantities of Ca and P are present in the extracellular fluids and whilst Ca is maintained within a very narrow range, the P concentration may vary from as low as 1 mg/l to in excess of 20 mg/l, depending on the dietary intake of the animal, and to a lesser extent on physiological activity (e.g. depletion during lactation).

A significant special function of the salivary glands of ruminant animals is to concentrate P in their copious secretions, often as much as 10-fold. This seems to be necessary to provide adequate P for ruminal microbial metabolism when dietary P is low, and for ruminal acid-base buffering. At the main Ca and P absorptive sites in the small intestine, which remain much more acidic in ruminant than in non-ruminant animals, the large quantity of P secreted by the saliva means that much more P than Ca must be absorbed and reabsorbed.

The skeleton provides an enormous reserve of both Ca and P in the animal, which can be drawn upon during a period of dietary deficiency. Although bone may be considered to be an inert portion of the animal, it is in fact highly labile; both the protein matrix and the hydroxyapatite crystals of bone are being continually replaced throughout the life of the animal. In mature animals such as wethers, the rates of bone accretion and resorption are equal. At times when dietary intakes are less than required (for example during early to mid lactation), more bone Ca and P is resorbed and less accreted to overcome the dietary deficiency (Braithwaite 1983*a*, 1983*b*; Ternouth and Budhi 1996). Subsequently, there are periods when the quantities accreted exceed those resorbed. This is a normal physiological activity within the animal, and is under a complex homeostatic mechanism involving at least three hormones. However, the resorption of P from bone is particularly vital to grazing cattle during the extended dry season in northern Australia.

The primary aim of the hormones regulating this homeostatic mechanism is to maintain the extracellular level of Ca within a narrow range of concentration for normal neuro-muscular action. The physiological effects of the hormones on extracellular P are secondary.

The buffering activity of the Ca and P reserves of bone makes the estimation of the requirements of all classes of animals particularly difficult, as there is normally no obvious effect of a dietary deficiency for weeks or months. The effect of a chronic P deficiency is to reduce food intake but this may not occur until a deficient diet has been fed to cattle for two months (Bortolussi *et al.* 1996) or to sheep for similar periods (Ternouth and Sevilla 1990*a*). In P-deficient sheep, Milton and Ternouth (1985) concluded that the reduction of food intake was metabolic in origin as the depletion of ruminal P alone did not reduce intake but reduction of both ruminal and plasma P did reduce intake. However, ruminal metabolism may still be involved in the effects of a P deficiency as P-deficient goats and sheep had less microbial protein passing to the duodenum (Gunn and Ternouth 1994*a*, 1994*b*). Clinical signs and detection of Ca and P deficiencies in the animal and the monitoring of adequate dietary levels of both minerals are discussed on pp. 125–128.

In 1991, AFRC revised its earlier factorial estimates of the Ca and P requirements of cattle and sheep (ARC 1965, 1980). In particular, the requirements of P were reduced but there was still a shortage of data upon which to base the estimates for cattle. The AFRC showed that the net maintenance requirements for both minerals should be based on DMI rather than weight and changed the absorption coefficients. Further, AFRC refined the Ca and P requirements for growth. Subsequently, Ternouth *et al.* (1996) and Ternouth and Coates (1997) have published data that show that the AFRC (1991) requirements of P by cattle, especially when consuming forage diets, were unnecessarily high. These data have been incorporated in the recommended requirements developed in the sections below.

Net requirements

Endogenous losses in faeces and urine

The urinary excretions of both Ca and P are 'overflow mechanisms' but the amount of both minerals excreted by this route is relatively small compared with faecal excretion. In the case of P, urinary losses only occur when the plasma inorganic P levels exceed 45–60 mg/l (Scott *et al.* 1984; Challa *et al.* 1989; Bortolussi *et al.* 1996; Dove and Charmley 2004). The recent data of Dove and Charmley (2004) indicate that urinary P excretion in sheep was <2.5% of P intake when P intake was <75 mg P/kg W, but then increased rapidly. At daily P intakes above 120 mg/kg W, urinary excretion of further P intake was complete. Urinary losses of P vary with the type of diet (Scott *et al.* 1984) and more is excreted when salivary flow is reduced (Tomas and Somers 1974). Because urinary excretion of both Ca and P occurs only when an excess is absorbed (and is overflowing), the net endogenous losses are considered to be zero. AFRC (1991) used the same reasoning to ignore urinary losses in estimating total endogenous losses.

The Ca and P in the faeces are from non-absorbed dietary and endogenous sources. In the case of Ca, absorption is closely regulated to maintain extracellular Ca concentration but most dietary P (and salivary P) is absorbed (and reabsorbed). Although Braithwaite's (1982) extensive sheep data clearly show that the dietary P absorption coefficient decreases at high dietary concentrations, when his data are limited to practical dietary concentrations, the coefficient is much less significant. Braithwaite's data may be compared with the subsequent young cattle data from his laboratory (Challa *et al.* 1989). The quantities of P that are absorbed in excess of requirements are mainly excreted in the faeces.

Many estimates of the faecal endogenous (FEL) losses of Ca and P have been made by extrapolation from observed losses over a range of intakes. Thus, endogenous losses and true absorption were measured at the same time and consequently were interdependent. However, isotope techniques, which distinguish FEL, have indicated poor relationships at least between endogenous faecal P and the true absorption of P (Field 1983). The extrapolation technique is also suspect because the absorption of Ca and P is under homeostatic control, mediated by the hormone 1, 25 dihydroxycholecalciferol. As a result, endogenous faecal losses must be estimated in animals fed deficient diets so that absorption is maximised, as is the re-absorption of endogenous secretions. To further complicate the determination, endogenous P is mainly of salivary origin, and salivary secretion rate is influenced by the quantity and physical form of the diet.

Endogenous faecal Ca values were assessed by the ARC (1980) as 16 mg Ca/kg live weight for both cattle and sheep. AFRC (1991), using the results of Braithwaite (1982), preferred estimates (g/d) based on the following equations for sheep and cattle, incorporating DMI (kg/d) and W (kg).

$$\text{FEL (Ca; sheep)} = 0.623\ \text{DMI} + 0.228 \tag{3.1}$$

$$\text{FEL (Ca; cattle)} = 0.66\ \text{DMI} + 0.0079\ \text{W} - 0.74 \tag{3.2}$$

Reliable assessments of FEL of P are the subject of much debate, due to the need to distinguish between obligatory FEL from losses that are non-obligatory, i.e. the excretion of the excess P that has been absorbed (Ternouth 1989; Ternouth *et al.* 1996). ARC (1980) used values of 10 and 12 mg/kg live weight for cattle and sheep respectively, but AFRC (1991) recognised the importance of DMI in assessing FEL as the losses are almost entirely of salivary origin and thus related to dietary intake (Ternouth and Davies 1985; Suttle 1987*b*), i.e. the values are not constant and must be related to an independent variable.

Given that bone reserves are mobilised during any period of dietary P deficiency, it is only after a substantial period of deficiency (at least four weeks) that FEL will be minimised and an assessment made of obligatory losses. A large bank of data (158 sets) taken from six experiments with housed and grazing cattle fitted these criteria (Ternouth *et al.* 1996). The data show that FEL is related to DMI but the correlation is improved when plasma inorganic P (PIP) levels of the cattle are included in the regressions. Because PIP is directly related to P intake, the data could be limited to those animals that had PIP levels between 30 and 50 mg/l, i.e. those that had been eating or grazing a low-P diet for an extended period of time. The regression for the obligatory losses (FEL, g/d) of P, for 58 sets of data from cattle weighing between 150 and 300 kg, is shown in equation 3.3.

$$\text{FEL} = 0.51\ \text{DMI} + 0.0037\ \text{W} \tag{3.3}$$

This equation gives lower values than the one adopted by AFRC (1991), which was developed from sheep data. It appears to be more in keeping with results of feeding experiments on breeding cattle in the USA (Call *et al.* 1978) and growing cattle in Australia (Little 1980). Equation 3.3 was subsequently compared with that obtained from a much more limited set of data from grazing breeding cattle (Ternouth and Coates 1997). Although the latter data set gave FEL values that were somewhat lower, it was concluded that the equation should be used for pregnant and lactating breeder cattle. As will be noted later, the requirements of high-producing dairy cattle are much higher than for breeder cattle. However there are no data that would suggest that the FEL is different from that given above.

Using the same reasoning for sheep is more difficult, as the research with sheep was undertaken much earlier, is fragmented and less capable of detailed analysis. The data of Ternouth (1989) showed that FEL was twice as high (equation 3.4) for sheep offered an 'adequate' P diet as for those on a 'low' P diet (equation 3.5).

$$\text{FEL} = 0.61\ \text{DMI} + 0.011\ \text{W} \tag{3.4}$$

$$\text{FEL} = 0.31\ \text{DMI} + 0.008\ \text{W} \tag{3.5}$$

AFRC (1991) also provides two equations for FEL, 'before' (equation 3.6) and 'after' (equation 3.7) adaptation to a low-P diet. Their equations, which were expressed initially in terms of food intake with a likely DM content of 880 g/kg, have been converted to DMI.

$$\text{FEL} = 0.69\ \text{DMI} - 0.06 \tag{3.6}$$

$$\text{FEL} = 0.24\ \text{DMI} + 0.26 \tag{3.7}$$

The data used for equation 3.6 were from sheep in substantial negative balance, i.e. they were resorbing and excreting skeletal P. After being held on the diet for a further three weeks they were in much less of a negative P balance and had lower FEL values (equation 3.7), i.e. they had adapted to the diet and the most easily reabsorbed pool of skeletal P had probably been exhausted. It is somewhat surprising that AFRC (1991) used the first equation to estimate the FEL for sheep (and cattle) in all the subsequent tables of their report as this equation appears to represent a transitory set of values. Their second equation (3.7) yields data very close to Ternouth's (1989) low-P diet equation (equation 3.5). Other comparable data from Ternouth's laboratory yield similar values for growing sheep (McLachlan 1992; Ternouth and Sevilla 1990*b*).

Later, Ternouth and Budhi (1996) found far higher FEL values for pregnant and lactating ewes, which fitted equation 3.4. Pregnant and lactating ewes frequently reabsorb more mineral from their bones than they require (Braithwaite 1983*a*, 1983*b*; Ternouth and Budhi 1996) and this mineral is excreted in the urine and faeces. This may well be the cause of the much higher figures recorded for these ewes and, on the present evidence, equation 3.4 has been **adopted** for pregnant and lactating ewes and equation 3.5 for other sheep. Rajaratne *et al.* (1990) found that dietary Ca and P levels during pregnancy had no effect on losses in early lactation. No immediate dietary compensation can be provided for lactating ewes and this must occur later in lactation or after weaning.

For their FEL values for P, AFRC (1991) have added a multiplier of 1.6 to allow for diets containing at least 50% roughage. This factor seems to be included because of the difference in FEL between a pelleted concentrate and a non-pelleted roughage diet in their sheep. However, in the cattle data collated by Ternouth *et al.* (1996), the values were not affected by whether the diet was chopped or grazed. Further, Ternouth (1989) found that grinding a roughage diet for sheep resulted in higher rather than lower FEL values. This factor of 1.6 has therefore been excluded for both cattle and sheep.

Growth

The net requirements of Ca and P for growth (G, g/d per kg LWG) are the rates of accretion in the body. For Ca, 0.99 is located in bone and AFRC (1991) developed new equations from a model based on bone growth, rather than from regressions from serial slaughter data (ARC 1980). A range of data was fitted to an allometric curve based on the assumptions that mature bone mass is 0.075 of mature live weight (A, kg) in sheep and 0.105 A in cattle.

$$G\ (Ca;\ sheep) = 6.75\ A^{0.28}\ W^{-0.28} \tag{3.8}$$

$$G\ (Ca;\ cattle) = 9.83\ A^{0.22}\ W^{-0.22} \tag{3.9}$$

The comparable requirements for P recognise that only 0.8 is located in bone and the following equations (AFRC 1991) include a requirement of 1.2 g P/kg gain in soft tissue.

$$G\ (P;\ sheep) = 1.2 + 3.188\ A^{0.28}\ W^{-0.28} \tag{3.10}$$

$$G\ (P;\ cattle) = 1.2 + 4.635\ A^{0.22}\ W^{-0.22} \tag{3.11}$$

The estimates of net requirements so obtained (g/kg LWG) are shown in Table 3.1. These values may be compared with the ARC (1980) fixed estimates of 11 g and 14 g Ca for sheep and cattle, respectively, and 6 g and 8 g P for sheep and cattle, respectively.

Pregnancy

The ARC (1980) values for the rates of accretion of Ca and P in the foetus and the uterine tissues are shown in Table 3.2. The assumption is made that during the first four months for cattle and two months for sheep, the conceptus does not accumulate sufficient Ca and P to require inclusion in the factorial equations. These values were not changed by AFRC (1991) and are **adopted** here.

Lactation

The net Ca and P requirements for lactation are the quantities secreted in the milk. Mean concentration values in bovine milk range from about 1.15 g Ca/kg and 0.90 g P/kg in Friesians (Rowland and Rook 1949) to about 1.45 g Ca/kg and 1.40 g P/kg in Jerseys (Reinart and Nesbitt 1956). ARC (1980) and Annenkov (1982*a*) found significant positive relationships between the Ca and butterfat content of bovine milk. In the subsequent calculations, a constant composition of 1.3 g Ca/kg is used so that the requirements calculated for the high-producing cows

Table 3.1. Estimates of the Ca and P contents of liveweight gain (g/kg) (AFRC 1991) in growing sheep and cattle of different mature weights (A kg)

	Weight (kg)	**Ca**			**P**		
		A			**A**		
		40	**50**	**60**	**40**	**50**	**60**
Sheep	10	10.0	10.6	11.1	5.9	6.2	6.5
	20	8.2	8.7	9.2	5.1	5.3	5.5
	30	7.3	7.8	8.2	4.7	4.9	5.1
	40	6.8	7.2	7.6	4.4	4.6	4.8
	50		6.8	7.1		4.4	4.5
	60			6.8			4.4
		400	**500**	**600**	**400**	**500**	**600**
Cattle	100	13.3	14.0	14.6	7.5	7.8	8.1
	200	11.5	12.0	12.5	6.6	6.9	7.1
	300	10.5	11.0	11.4	6.1	6.4	6.6
	400	9.8	10.3	10.7	5.8	6.1	6.3
	500		9.8	10.2		5.8	6.0
	600			9.8			5.8

provide an extra margin of safety against a deficiency. A mean P concentration in cow's milk of 1 g/kg is used. These values are marginally higher than those used by the NRC (1978, 1984) for dairy and beef cattle, by Annenkov (1982*a*), and for all except Jersey cows by ARC (1980). Values of 1.9 g Ca/kg and 1.5 g P/kg milk are **adopted** here for sheep (ARC 1965; Annenkov 1982*b*), and are somewhat higher than ARC (1980).

Table 3.2. Estimates of Ca and P accretion (g/d) in the whole conceptus of cattle and sheep (ARC 1980)

Stage of pregnancy (months)	Conceptus gain (g/d)	Ca (g/d)	P (g/d)
Cattle			
5 and 6	290	1.4	0.9
7	430	3.2	1.9
8	540	5.2	3.1
9	680	7.9	4.8
Sheep			
3	33	0.15	0.15
4	59	0.58	0.35
5	96	1.14	0.50

Availability and absorption

The quantity of a mineral excreted in the faeces is the sum of: (*a*) the unavailable dietary mineral; (*b*) available but unabsorbed dietary mineral; and (*c*) endogenous mineral.

The dietary mineral available for absorption is the amount released during the processes of digestion and appears to be in the same pool as the endogenous mineral at the absorptive sites in the gastro-intestinal tract.

There is variation among feeds and mineral supplements in the availability of their Ca and P (Underwood and Suttle 1999), but because there is so little information on this matter it is not possible to make allowance for such variation in estimates of requirements (Suttle 1987*b*). A portion of the available dietary and endogenous P in the gastro-intestinal pool is incorporated into the microbial cell mass in the rumen.

Numerous studies have been made of factors affecting Ca and P absorption (e.g. Care *et al.* 1980; Scott *et al.* 1984). Calcium absorption is subjected to precise homeostatic control so that the dietary intake and absorption coefficient are inversely related (Braithwaite 1983*a*). Because so much P is recycled in the saliva into the gastro-intestinal tract, and salivary secretion is related to plasma inorganic P and hence to dietary P, dietary absorption coefficients are measurements of 'damped' homeostatic mechanisms and consequently are not easy to interpret. Nevertheless, there is an inverse relationship between intake and the absorption coefficient of P (Braithwaite 1983*b*; Dove and Simpson 1997).

The true absorption coefficients adopted by the AFRC (1991) were little changed from those proposed by ARC (1980), except that the values for P depend on the quality of the diet and not on the age of the animals. Coefficients of 0.68 and 0.70 were recommended for Ca and P, respectively, in both sheep and cattle on high-quality diets and the value of 0.68 for Ca is **adopted** in this report for sheep and cattle. Although AFRC (1991) adopted lower coefficients of 0.58 and

0.64 in sheep and cattle, respectively, for P absorption on roughage diets, Ternouth and Budhi (1996), Ternouth *et al.* (1996) and Ternouth and Coates (1997), have shown that absorption coefficients for P are >0.75 for sheep and cattle unless the diet has an extremely low concentration of P. As a conservative step, a coefficient of 0.7 is **adopted** in this report for P absorption in sheep and cattle on all diets.

For milk-fed ruminants, absorption coefficients of 0.95 for both Ca and P are generally used (ARC 1980). True absorption coefficients approaching 1.0 have been reported in milk-substitute-fed calves (Ternouth *et al.* 1985). As milk contains in excess of 10 g/kg DM of both minerals (Table 3.3) and because calves and lambs in Australia, virtually without exception, are either suckled or are hand fed on milk-based diets, their requirements have not been calculated.

Recommended allowances

Based on the net requirements and the availability factors, Tables 3.3 and 3.4 show a number of examples of the suggested allowances of Ca and P for sheep and cattle, both as g/d and as concentrations of the element in the diet (g/kg DM). AFRC (1991) found from field tests that it is unnecessary to include a safety factor, a conclusion that is supported, in the case of P, by Ternouth and Coates (1997) despite their lower estimates of requirements.

The Ca allowances for the maintenance and growth of cattle are higher than ARC (1980) and NRC (1984, 1996, 2001) but lower than ARC (1965). The P allowances are lower than AFRC (1991) due to the downward revision of the value for endogenous faecal P on roughage diets and the higher estimate of P absorption. The estimates of the additional quantities required for pregnancy and lactation are similar to those recommended by ARC (1980) and NRC (1984, 1996, 2001). These assume that first-calf heifers are continuing to grow at rates of between 0.4 and 0.8 kg/d, but that with mature cows there is no liveweight gain.

Table 3.3. Recommended Ca and P allowances for sheep[A]

	Weight (kg)	Gain (g/d)	Intake[B] (kg DM)	Ca allowance (g/d)	Ca allowance (g/kg DM)	P allowance (g/d)	P allowance (g/kg DM)
Growing	20	100	0.61	2.18	3.57	1.28	2.10
weaner	20	200	0.95	3.77	3.97	2.37	2.50
	30	100	0.84	2.25	2.68	1.44	1.72
	30	200	1.25	3.77	3.02	2.55	2.04
	40	100	0.97	2.28	2.35	1.53	1.58
	40	200	1.45	3.78	2.60	2.66	1.84
Adult	50	0	0.69	0.97	1.40	0.60	0.87
		Week of gestation					
Pregnant[C]	50	14	0.69	1.70	2.46	1.10	1.59
	50	21	0.96	3.83	3.99	1.87	1.95
		Milk (kg)					
Lactating[D]	50	1.7	1.77	6.71	3.79	5.31	3.00

[A] A sheep with a mature weight of 50 kg.

[B] Using a temperate pasture diet with a dry matter digestibility of 0.74.

[C] A ewe maintaining a maternal weight of 50 kg.

[D] In general, add 2.8 g Ca per day and 2.1 g P per day for each kg milk.

Table 3.4. Recommended Ca and P allowances for cattle[A]

	Weight (kg)	Gain (g/d)	Intake[B] (kg DM)	Ca allowance (g/d)	Ca allowance (g/kg DM)	P allowance (g/d)	P allowance (g/kg DM)
Growing	150	0.5	2.9	9.2	3.15	6.2	2.15
weaner	150	1.0	4.1	16.0	3.90	10.9	2.66
	300	0.5	4.4	11.5	2.62	7.4	1.67
	300	1.0	5.7	17.7	3.10	11.7	2.06
	400	0.5	5.7	13.7	2.40	8.5	1.49
	400	1.0	7.5	20.0	2.66	13.2	1.77
Adult cow[C]	500	0.0	4.4	9.0	2.04	4.3	0.97
		Milk (kg)					
Lactating[C,D]	500	18	9.0	47.9	5.32	34.5	3.84
	500	22	13.5	59.9	4.44	44.7	3.31
	500	32	16.8	82.2	4.89	62.3	3.71

[A] A cattle type with a mature weight of 500 kg.
[B] Using a temperate pasture diet with a dry matter digestibility of 0.74.
[C] During pregnancy, add the following allowances (g/d):
month of gestation 5–6: 2.3 g Ca; 1.1 g P
7: 5.3 g Ca; 2.2 g P
8: 8.7 g Ca; 3.6 g P
9: 13.2 g Ca; 5.7 g P
[D] In general, add 1.9 g Ca per day and 1.4 g P per day for each kg milk.

These tables show just a few examples of the almost infinite range of instances for particular animals. A spreadsheet program freely available at www.pi.csiro.au./grazplan enables the user to obtain estimates of requirements for any specific case.

Grazing cattle and sheep

A general problem with grazing animals is the difficulty of measuring the amounts of Ca and P in their diets unless specialised techniques are used. Under intensive grazing, estimates of diet composition are possible but in extensively grazed areas, when there is a much greater likelihood of deficiencies, this is not the case. Indirect methods of assessing the adequacy of the diet and body reserves of the animals are required and these include analyses of blood, excreta and bone.

Calcium

The Ca concentrations required in the diet of grazing sheep and cattle vary from about 2 to 4 g/kg DM (Tables 3.3 and 3.4) and only exceed these values for lactating cows. Consequently, it is unusual for grazing ruminants to be subjected to a shortage of Ca except when heavy supplementary feeding is practised, because forages normally contain adequate concentrations (Underwood 1981; Norton 1982). When feeding cereal grain diets for extended periods, for instance in drought, the addition of 15 kg ground limestone per tonne is recommended because grains contain only *c.* 1 g Ca/kg DM. Franklin *et al.* (1948) reported severe hypocalcaemia, loss of appetite, stunted growth, dental abnormalities and high mortality in sheep fed 50:50 mixtures of wheaten chaff and cereal grains (maize, oats or wheat). Peet *et al.* (1983) reported similar problems in sheep fed similar diets while awaiting export. The supplementary Ca has

been shown to have a positive effect upon feed intake (Peet *et al.* 1983) but this may be due to its effect upon ruminal digestion rather than a response to a Ca deficiency.

The need for supplementary Ca is reduced if the animals are able to gain some feed from the drought-affected pastures. Although the Ca concentration in herbage generally decreases with advancing maturity, it increases when it becomes dry and senescent. This is because the mineral is principally associated with the cell wall material. In general, if pastures contribute more than 0.25 of the dry matter intake, Ca supplementation is probably unnecessary although it is still a good and cheap insurance against deficiency, especially in lactating animals (Langlands *et al.* 1967).

Although grazing animals rarely suffer from a Ca deficiency, there have been reports from overseas of low productivity and osteotrophic diseases in high-producing dairy cows and other livestock grazing quick-growing grasses containing less than 2.0 g Ca/kg DM. Such grasses grow on acid, sandy or peaty soils in humid tropical areas (Underwood 1981). Elsewhere, the animal chiefly at risk is the high-yielding dairy cow.

Acute hypocalcaemia, characterised as 'milk fever' or 'parturient paresis', is not uncommon in cows at pasture within the first three days after calving when the requirement for Ca has suddenly and substantially increased. The incidence in beef cows is uncertain. A comparable condition of hypocalcaemia in pregnant ewes known as lambing sickness occurs widely (Underwood 1981; Caple *et al.* 1988*b*). The hypocalcaemia results from inadequate gastro-intestinal absorption and bone re-absorption to satisfy the Ca requirements of the conceptus and for milk production.

A substantial reduction in the incidence of hypocalcaemia can occur when low-Ca diets are fed during late pregnancy. This appears to be associated with the activation of hormones that control intestinal absorption and of osteoclasts associated with bone resorption (Horst 1986; McLachlan 2004). Absorption from the small intestine is also affected by the acid-base balance in the arterial blood and there is good evidence that reducing the ratio of cations to anions in the diet will reduce the risk of hypocalcaemia (Schonewille *et al.* 1994). Although the provision of anionic supplements, e.g. chlorides or sulfates of Ca or Mg, for three weeks before and after parturition in dairy cows is commonly practised in the USA, tests in pasture-based dairy systems in Australia have, so far, shown little benefit (McNeill *et al.* 2002), possibly because K levels in the pasture diet are too high for the supplements to be effective. In sub-tropical pastures, high levels of chloride may also make the use of anionic supplements ineffective (McLachlan 2004). Current recommendations include the reduction of K levels in the diet, through fertiliser and feed selection, and attention to the adequate replenishment of bone Ca in the dry period.

Osteoporosis in lambs aged from 10 weeks to 15 months has been observed in south-eastern Australia (Palmer 1969; Mason and Koen 1985). The causes include generalised malnutrition, Ca deficiency (Palmer 1969), Cu deficiency (Mason and Koen 1985), vitamin D deficiency (Mason and Koen 1985) and intestinal parasitism (Sykes 1982). The level of milk intake influences the time at which the young lamb commences grazing, and the quantity of pasture ingested before weaning (Hodge 1966). If lambs are unable to obtain sufficient Ca from pasture then bone structure may be compromised (Heath and Caple 1988). It is the rapidly growing proximal limb bones, such as the femur, that are most affected (Hodge *et al.* 1973).

Phosphorus

The recommended minimal P concentrations (Tables 3.3 and 3.4) range from 0.9 to 2.7 g P/kg DM, although higher values are required for lactating ewes and cows. The P content of plants

decreases with increasing maturity because the mineral is continuously transferred to new growth. There is less likelihood of a deficiency in temperate than in tropical regions. Tropical forages have a lower P content (Norton 1982) because the soils are often low in phosphate, the use of fertilisers is often uneconomic, and the forages mature and senesce more rapidly than temperate species. The introduction of more productive plant species that can tolerate low soil phosphates, such as *Stylosanthes* spp., may compound the problem. In these northern areas of Australia, dietary deficiencies of both N and P occur so the supply of additional dietary N exacerbates the P deficiency (Hendricksen *et al.* 1994).

Phosphorus deficiency occurs in grazing cattle but the statement by McDonald (1968) that 'there has been no clear demonstration of a primary P deficiency in grazing sheep' has not been clearly refuted. However, in the animal house the feeding of diets containing low levels of P to growing cattle and sheep leads to a reduction in DMI in *c.* two months (Ternouth and Sevilla 1990*a*, 1990*b*: Bortolussi *et al.* 1996). The P intake of grazing sheep may be greater than that of cattle because of the sheep's superior ability to select the smaller growing parts of the plant. It has also been suggested that the smaller proportion of the year that ewes spend lactating, compared with cows, means that more time is available for the replenishment of their depleted P reserves (Underwood and Suttle 1999).

The likelihood of animals suffering from long-term, although seasonal, P inadequacy may be estimated from maps of P levels in soils (McCosker and Winks 1994). In northern Australia, soils with less than 4 ppm soil P are considered acutely deficient; those with 4–8 ppm are considered to be deficient or marginally deficient. As there are large areas of such soils in the extensive cattle-grazing country of northern Australia and these areas are unlikely to ever receive P fertiliser, the timing, amount and form of supplementation are important considerations.

A reduction in feed intake is the primary effect of P deficiency. Prolonged deficiency results in a reduced growth rate and there is no conclusive evidence of a specific effect on reproduction or on lactation. Impairments of these functions are probably a consequence of inadequate supplies of energy and/or protein. The ultimate effect of chronic P deficiency is upon bones; both in the animal house and the field, osteoporosis and bone fragility have been observed (Bortolussi *et al.* 1996). The associated 'peg-leg' condition, in which cattle walk with a stiffened gait is also seen, as well as pica (a depraved appetite) for soil, wood, bone etc. (McCosker and Winks 1994).

These clinical signs are not specific to a P deficiency and the most useful sign of a dietary P deficiency is plasma inorganic P (PIP). PIP levels in cattle and sheep are directly related to dry matter intake (Bass *et al.* 1981; Ternouth 1989; Ternouth and Sevilla 1990*a*, 1990*b*) and the level of Ca in the diet does not affect the relationship. Underwood and Suttle (1999) state that marginal bands for P in blood plasma are 31–47 mg/1 (1.0–1.5 mmol/l) for adults and somewhat higher, 40–60 mg/l (1.3–1.9 mmol/l), for lambs and calves. Plasma levels are related to recent P intake (Cohen 1975; Ternouth *et al.* 1980; Braithwaite 1985) and there are constraints associated with animal stress, time of sampling, and nutrient interactions on the interpretation of PIP values. PIP levels are poorly related to skeletal reserves, except when the deficiency has existed for many months.

The analysis for P of herbage, faecal or urine samples, and especially faecal 'grab' samples, has been advocated. Renal excretion appears to be an 'overflow' mechanism by which ruminants can excrete P when plasma levels rise above 45–60 mg/l. Because the quantity of urine secreted by individual animals is highly variable, urine testing is unlikely to be useful. Faeces do not have this disadvantage. Belonje and Van der Berg (1980) found a close relationship between the P

concentrations in the feed and faeces of sheep, with faecal concentrations below 2 g P/kg DM when a P-deficient diet was fed. In sheep, P concentration is closely related to P intake (Dove and Simpson 1997; Dove and Charmley 2004). In cattle, Cohen (1974) found that the relationship between P intake and faecal P concentration was markedly improved when diet digestibility was added as a second independent variable. Long-term recommendations for the northern cattle industry have been formulated, based on these faecal P levels (McCosker and Winks 1994). However, techniques based on the measurement of PIP and plasma urea N together (Ternouth *et al.* 1993; Bortolussi *et al.* 1996) may prove to be simpler and more useful as both deficiencies co-exist in the field.

Techniques that best measure the reserve status of the animal are those associated with bone. Bone ash, Ca or P can be monitored as a measure of the reserves of extensively grazed animals, but it is many months before depletion is observed (Belonje and Van der Berg 1983). Rib-bone biopsy was developed by Little (1972) and used by Read *et al.* (1986*c*). An analytical improvement involving the use of the phosphorus/nitrogen ratio was made by Ternouth *et al.* (1980). Little (1983, 1984) used the simpler technique of measuring costal cortical bone thickness. Non-invasive techniques have been developed, for instance radiographic (Bass *et al.* 1981) and dichromic neutron absorption (Zetterholm and Dalen 1978) techniques to examine the bovine tail, and a neutron activation technique for the metatarsus of cattle and sheep (Ternouth *et al.* 1980). However, all these bone techniques have a poor degree of discrimination; observable bone changes occur only after an extended period of P deficiency during which time feed intake, and consequently animal production, are depressed. There is little evidence to suggest that hair, skin or soft tissues would be any more useful in determining dietary P intake or body reserves (Cohen 1975).

Dietary P deficiency may be rectified by direct supplementation with a range of materials including monosodium phosphate and monoammonium phosphate (Cohen 1975, McCosker and Winks 1994). Commercial phosphoric acid has been added to drinking water, but in a number of studies there appeared to be some deleterious effects (Gartner *et al.* 1980). Superphosphate with a low fluorine content can be used, but this and other P supplements made from phosphate rocks may contain undesirable amounts of cadmium (see p. 171).

Chlorine

Chloride is the most abundant anion in the body. The majority is found in the extracellular fluids, including blood plasma and cerebrospinal fluid, and normal plasma concentrations are within the range of 3.3–3.9 g Cl/l (93–110 mmol/l). Its functions include, with Na and K, the regulation of osmotic pressure and acid-base equilibrium. As hydrochloric acid secreted into the abomasum it also has an important role in digestion.

The ARC (1980) states that there appear to be highly efficient renal mechanisms for conserving Cl, so that obligatory losses in urine are small, but it estimates that the dermal loss from a 500 kg cow may be 0.4 g Cl/d in temperate conditions and increase to 1.6 g Cl/d in tropical conditions. Substantial quantities are secreted in milk, around 1.2 g/l of cow milk but less with ewes, around 0.8 g Cl/l (Ashton and Yousef 1966). Lactose and Cl concentrations are negatively correlated, reflecting regulation of osmolality, and this probably accounts for the lower concentration in ewe milk, which contains more lactose. Chlorine concentration increases with advancing lactation in association with the normal decrease in lactose, and it increases during

mastitis when lactose concentration is also reduced. In growing animals the ARC (1980) estimates there is 0.8–1.0 g Cl/kg empty body gain.

Despite the major importance of Cl, deficiencies have been observed only when animals, even lactating cows (Fettman *et al.* 1980), have been given carefully prepared low-Cl diets. Deficiencies are most unlikely in practice because all feeds, including pasture (Fleming 1965), contain Cl in amounts at least sufficient to meet requirements. The estimates of requirements (g Cl/kg DM) made by Towers (1983) are similar to those of the ARC (1980) and are in the ranges of 0.25–0.50 for growing sheep and for dry or pregnant ewes; 0.8–1.0 for lactating ewes; 2.0–2.4 for lactating cows; and 0.67–1.00 for all other cattle. The matter of excess chloride (with other minerals) in saline water and feed is discussed in *Salinity* on p. 195.

Cobalt and vitamin B_{12}

The need for cobalt by ruminants was first observed by Lines (1935) and Marston (1935). It is required for the synthesis of vitamin B_{12} by the ruminal micro-organisms and it is the vitamin, not the element, which is required by the host tissues.

It is generally accepted that under grazing conditions, sheep are more susceptible to Co deficiency than cattle, deer or goats (Clark *et al.* 1987) and that with all species the young are more susceptible than the mature animal (Andrews 1971). The susceptibility of sheep may result from the role of B_{12} in the microbial synthesis of methionine, required for wool growth. Marginal Co deficiency is probably more widespread than clinical deficiency and, because it may go undetected, of greater economic significance (Judson *et al.* 1987). A map showing locations in Australia where livestock are at risk from Co deficiency is given in a review by Peverill and Judson (1999).

Consequences of cobalt deficiency

Features common to Co deficiency in all ruminants are a loss of appetite and lethargy, progressing to wasting of musculature, and death. There are no specific signs upon which an unequivocal diagnosis can be made. In sheep, signs include weeping 'rheumy' eyes, scaly ears, pale and tender skin and paleness of mucous membranes from anaemia. Co deficiency in ewes can result in a high perinatal loss of lambs (Fisher and MacPherson 1986) and in reduced milk production (Quirk and Norton 1987). In cattle, loss of coat colour, reduced milk production and eventually anaemia have been noted.

Inappetence and loss of condition invariably precede any marked degree of anaemia. Filmer (1933) reported the anaemia to be normocytic and hypochromic in lambs, and microcytic and hypochromic in calves. It is now considered that the anaemia in sheep is normocytic and normochromic due to bone marrow hypoplasia (Smith *et al.* 1950; Gawthorne *et al.* 1966; Sheriff and Habel 1976). In cattle, Neal and Ahmann (1937) observed a microcytic and hypochromic anaemia and Judson and Gifford (1979) a compensated microcytic normochromic anaemia. In goats, various forms of anaemia have been observed: macrocytic normochromic anaemia (Mgongo *et al.* 1981) a microcytic hypochromic anaemia (Johnston *et al.* 2004) and a microcytic normochromic blood picture (Mburu *et al.* 1993). These may be related to age and severity of deficiency, or both.

Gross pathological alterations of Co-deficient animals are typically those of general inanition, sometimes accompanied by fatty degeneration of the liver. Degenerative changes in the

liver, central nervous system and muscle of severely deficient sheep have been described by Fell (1981). Enhanced susceptibility to infection and impaired immunity have been observed (MacPherson *et al.* 1976; Fisher and MacPherson 1986; MacPherson *et al.* 1987) as have associations with a number of diseases including cerebrocortical necrosis or polioencephalomalacia in sheep (Hartley *et al.* 1962; MacPherson *et al.* 1976), white liver disease in sheep and goats (Sutherland *et al.* 1979; Black *et al.* 1988), and phalaris staggers in sheep and cattle (Lee and Kuchel 1953). Gallagher *et al.* (1966) classified phalaris staggers as a nervous form of toxicity caused by tryptamine alkaloids in the plant. However, the primary cause of peracute or acute phalaris toxicity, the cardiac, sudden-death syndrome (Bourke *et al.* 1988), is N-methyltyramine (Anderton *et al.* 1994). Cobalt is not protective against the acute, sudden-death form of toxicity. Weekly oral doses of 28 mg Co (Lee *et al.* 1957*a*), administration of a Co pellet (Dewey *et al.* 1958) or pasture sprays (Bourke 1998) have been found to protect sheep against phalaris staggers; vitamin B_{12} injections are ineffective (Lee *et al.* 1957*b*).

Factors affecting the synthesis of vitamin B_{12}

An absolute requirement of the ruminal micro-organisms for Co has not been determined. The growth and metabolic activity of some microbial species have been shown to be affected by Co supplementation (McDonald and Suttle 1986). Kennedy *et al.* (1996) found a reduction in the conversion of succinate to propionate by ruminal micro-organisms in sheep on barley-based diets containing <20 μg cobalt/kg DM whereas Tiffany *et al.* (2006) reported that that Co levels of 10–15 μg/kg DM resulted in adequate B_{12} production to meet ruminal microbial requirements on a high-concentrate diet in a continuous culture fermentor. The main role of Co is in its incorporation into B_{12} and analogues of this vitamin. Bacteria produce a number of B_{12} analogues that are active in micro-organisms but appear to be inactive in animals (Gawthorne 1970; Schneider 1987). The two active forms, methylcobalamin and adenosylcobalamin have quite different functions in bacterial metabolism. The former acts as a coenzyme in methyltransfer processes involved in the synthesis of methane, acetate and methionine and the latter as a coenzyme of methylmalonyl-CoA mutase that is involved in the formation of succinate from propionate in the liver (Stroinski and Schneider 1987). It appears that the accumulation of propionate when adenosylcobalamin is deficient, leading to depressed appetite and growth, is the first limiting of the two functions (Kennedy *et al.* 1992), occurring before evidence of defective methylation. The dysfunction in methylation caused by a deficiency of methylcobolamin leads to a rise in plasma homocysteine (Kennedy *et al.* 1992), and this is a useful marker for B_{12} status (see below).

The nature of the diet, especially the Co content, can affect the production of vitamin B_{12} in the rumen and the relative proportions of B_{12} to analogues synthesised. Estimates of B_{12} production in sheep range from about 0.05 mg/d on diets with less than 0.05 mg Co/kg DM to about 1.6 mg/d on diets containing *c.* 1 mg Co/kg DM (Smith and Marston 1970; Hedrich *et al.* 1973). The efficiency of conversion of dietary Co to B_{12} appears to increase with decreasing intake of Co; Smith and Marston (1970) reported a conversion of 0.13 in sheep on a Co-deficient diet but only 0.03 when Co intake was adequate.

Rations of high energy content (M/D) have been reported to depress B_{12} production and favour the synthesis of analogues in sheep (Elliot *et al.* 1971; Sutton and Elliot 1972; Bigger *et al.* 1976) and cattle (Walker and Elliot 1972; Santschi *et al.* 2005). MacPherson and Chalmers (1985) were unable to demonstrate changes with M/D in plasma B_{12} levels in cattle but the levels

may not be a sensitive index to changes in the ruminal production (see below). A smaller proportion of B_{12} analogues to vitamin B_{12} was observed in the rumen of sheep on pasture than in sheep given a roughage-gluten diet (Smith and Marston 1970) and this proportion decreased in sheep as dietary Co was reduced (Gawthorne 1970).

It appears that there is extensive destruction in the rumen of orally administered B_{12} and that most of the vitamin passing from the rumen is bound to micro-organisms (Smith and Marston 1970; Zinn *et al.* 1987). Much of the vitamin is presumed to be liberated in the acid environment of the abomasum, and it is absorbed mainly from the distal part of the small intestine (Girard and Rémond 2003). Estimates from sheep of the proportion absorbed vary from about 0.05–0.40 (Smith and Marston 1970; Elliot *et al.* 1971; Hedrich *et al.* 1973; Rickard and Elliot 1978). Absorption appears to be enhanced by greater ruminal synthesis and by slower rates of passage of digesta. Zinn *et al.* (1987) estimated that almost half of the B_{12} entering the small intestine of cattle was absorbed, and Halpin *et al.* (1984) reported significant quantities of B_{12} analogues, up to 0.50 of total B_{12}, in the blood of cows on diets of high energy content; only small amounts of analogues were found in sheep blood.

Requirements and assessment of dietary adequacy

The tissue requirements of ruminants for vitamin B_{12} remain undefined. Marston (1970) and Smith and Marston (1970) estimated that the requirement of mature sheep is 11 μg daily; no estimates are available for cattle. It can be expected that requirements will increase in rapidly growing animals and during pregnancy and lactation. The transfer of B_{12} to the foetus has been observed in sheep (Halpin and Caple 1982), and B_{12} concentrations appear to be high in colostrum and in milk during the early stages of lactation (Walker and Elliot 1972). Milk vitamin B_{12} levels appear to be responsive to Co supplementation (Skerman *et al.* 1961) and hence its assay is of diagnostic value (Judson *et al.* 1997; Judson *et al.* 2002).

The potentially limiting reactions in which the vitamin is involved occur in the liver, although it does have other metabolic roles elsewhere, for example in polymorphonucleated cells and haematopoietic tissue. Liver B_{12} rather than Co concentration is therefore preferred as an indicator of the Co adequacy of the diet. In Co-deficient sheep, or those given oral doses of Co only, about one-third of the liver Co can be accounted for as vitamin B_{12} (Andrews *et al.* 1960). Mitsioulis *et al.* (1995) found that in cattle, about 60% of the liver Co was associated with B_{12} but this percentage decreased with liver Co levels above 3 μmol/kg DM. It is generally considered that tissue Co is not available for B_{12} synthesis in the rumen and hence is of little physiological significance, although there is evidence that trace amounts of tissue Co may enter the stomach of sheep (Grace 1975).

Because liver B_{12} becomes depleted prior to the onset of sub-clinical as well as clinical Co deficiency, its assay is of diagnostic value. However, the level responds more slowly to a fall in Co intake than serum or plasma B_{12} levels in sheep, indicating that the liver should not be regarded as a storage organ for B_{12} (Underwood and Suttle 1999). Serum levels therefore provide a more sensitive index to changes in dietary Co intake when this is low (Sutherland 1980). Serum B_{12} concentrations can vary markedly between animals within a flock and so it is necessary to sample a number of animals to assess the Co adequacy of the pasture. It has also been shown with sheep that prolonged yarding can affect serum B_{12} concentrations (Millar *et al.* 1984).

Vitamin B_{12} concentrations in serum and liver may indicate status (Table 3.5) and have been related by Clark *et al.* (1985, 1989) to the probability of a response by sheep to Co

supplementation. However, technical problems have been encountered in some assay procedures for B_{12} in the blood of cattle (Judson *et al.* 1982; Millar *et al.* 1984; Carlos *et al.* 1987; Schultz 1987; Judson *et al.* 2002). Moreover, plasma B_{12} values do not appear to be as responsive in cattle as in sheep to small changes in Co availability, and MacPherson (1981) has raised doubts about their value as an index of dietary Co adequacy for cattle. Low plasma B_{12} values in cattle do not exclude the possibility that cattle have adequate liver levels (Judson *et al.* 1997). Reference values have not been established for goats but there is enough evidence to suggest that normal values are lower than those found in sheep.

There has been increasing interest in developing improved diagnostic tests for assessing the adequacy of Co intake. Markers of metabolic disturbance may prove effective in detecting marginal or early stages of a deficiency. Loss of activity of vitamin B_{12}-dependent pathways will interrupt the metabolism of propionate and result in an increase in methylmalonic acid (MMA). The increase in MMA in serum is a useful diagnostic test, occurring in animals with <200 pmol B_{12}/l serum (Rice *et al.* 1987). Individual MMA plasma values of 5–20 μmol/l. and group mean values of 5–10 μmol/l indicate marginal Co status in growing or mature animals (Underwood and Suttle 1999). Stangl *et al.* (2000) have shown that the combination of MMA with plasma homocysteine, which also increases in B_{12} deficiency, provides a useful diagnostic tool for defining Co requirement in fast-growing cattle. However, plasma MMA is not as responsive to B_{12} deficiency in sucking lambs as in weaned lambs and also, in severely Co-deficient sheep, plasma MMA may return to almost normal values (Kennedy *et al.* 1994).

Dietary requirements

There have been a considerable number of reports on the Co content of pasture and semi-synthetic feeds that have been inadequate to meet the requirements of livestock, particularly sheep. In reviewing this evidence, the ARC (1980) agreed with the suggestion of Andrews (1965*a*) that pastures, or diets of conserved roughage, with 0.11 mg Co/kg DM will meet the requirements of sheep and cattle in most circumstances. However, on high-energy diets, requirements may be considerably higher. Schwarz *et al.* (2000) found that the dietary requirement to maximise feed intake and growth in cattle on a corn silage-based diet was 0.16–0.18 mg Co/kg DM.

Estimates of the Co requirements or the prediction of Co deficiency in grazing livestock cannot confidently be based on pasture Co concentrations because soil ingestion can be a significant source of Co, though there is substantial variation between soil types and in the availability of Co to the animal (Underwood and Harvey 1938; MacPherson *et al.* 1978; Clark and Millar 1983; McDonald and Suttle 1983; Brebner and Suttle 1987). The increased vitamin B_{12} status of sheep at high stocking rate (McQueen 1984; Judson *et al.* 1985) may reflect increased soil intake. Assay of faecal samples may provide an estimate of Co intake of livestock at pasture.

Selective grazing can alter the Co intake of the animal. It is generally considered that legumes are richer in Co than grasses (Gardiner 1977) although when the soil is Co-deficient there may be little difference (Andrews 1966). Pasture Co concentrations vary with season, tending to be lower when there is rapid pasture growth (Andrews 1966), and decrease as the plants mature (Fleming and Murphy 1968).

In many field investigations the criterion of Co deficiency has been whether the productivity of the animal will respond to Co or vitamin B_{12} supplementation. This can be a slow and costly exercise. The assessment of Co requirements of livestock should be based on biochemical or pathological changes, which are much more sensitive indicators than are measures of

productivity. Table 3.5, adapted from Underwood and Suttle (1999), sets out marginal bands for the most common biochemical indices used to assess the mean Co and B_{12} status of groups of ruminants.

Table 3.5. Marginal bands for a range of indices used to assess the Co and B_{12} status of groups of animals (adapted from Underwood and Suttle 1999)

			Marginal status[A]
Diet	Sheep and goats		0.05–0.07 mg/kg DM
	Cattle		0.04–0.06 mg/kg DM
Plasma B_{12}	Sheep: suckled	230–350 pmol/l	312–474 ng/l
	weaned	336–500 pmol/l	455–678 ng/l
	Cattle: suckled	30–60 pmol/l	41–82 ng/l
	weaned	40–80 pmol/l	54–108 ng/l
Liver B_{12}	All species	200–220 nmol/kg FW[B]	379–461 µg/kg FW
Milk B_{12}	Cattle	250–500 pmol/l	339–678 ng/l
Plasma MMA[C]	All weaned ruminants	5–10 µmol/l	6.8–13.6 mg/l

[A] Observed mean values which lie within a band indicate the possibility of sufficient individuals benefiting to justify supplementation for all. Individual values below the lower limit (or above the upper limit for MMA) indicate the possibility of dysfunction.
[B] Fresh weight.
[C] Methylmalonic acid.

Cobalt or B_{12} supplementation

In areas where the feed supply has an inadequate concentration of Co, deficiency symptoms may be prevented in a number of ways. Cobalt may be applied to the pasture as $CoSO_4$ at a rate of about 1.5 kg/ha (mixed with fertiliser) every three to four years, except on calcareous soils, which fix Co. An alternative is direct supplementation with Co salts (sulfate or carbonate) in drinking water, mixed with feeds or incorporated in salt licks. For free-grazing animals, a more effective solution is to insert into the rumen a slow-release pellet or 'bullet' that provides a steady supply of Co over several years, maintaining a concentration in the rumen of >5 µg/l. Pellets in which the matrix is a glass bolus (Judson *et al.* 1988) do not develop the calcium phosphate coating that requires an accompanying steel screw for its removal when the more common bullets made of 30% cobaltic oxide in iron powder are used. Bullets may be formulated with additional minerals such as Cu and Se for specific situations. A recent development is the subcutaneous injection of microencapsulated B_{12} in an oil carrier (Grace 1999). This is effective for eight months in lambs and at least three to four months in calves, much longer than earlier, aqueous carrier, preparations. See Judson (1996) for a detailed review of Co and B_{12} supplementation.

The commonly accepted strategies in Australia are to use intraruminal pellets for weaned animals and B_{12} injections for young animals, which are particularly susceptible to deficiency from about one month of age (Judson *et al.* 2002).

Cobalt toxicity

It appears from the limited information on Co toxicity that ruminants, particularly sheep, may tolerate dietary Co levels well in excess of their requirements. Daily doses of a soluble Co salt providing 3–4 mg Co/kg W have been reported to be tolerated by sheep for periods of up to 10

weeks (Becker and Smith 1951; Corrier *et al.* 1986), whereas young cattle appear to tolerate up to about 1 mg Co/kg daily for short periods (Keener *et al.* 1949). Daily doses above 1 mg Co/kg W to cattle and 4 mg Co/kg W to sheep can produce symptoms not unlike those of Co deficiency and include depressed appetite, loss in body weight and listlessness (Josland 1937).

Single oral doses of 7–16 mg Co/kg W are tolerated by sheep (Stewart *et al.* 1955) but doses in excess of 40 mg/kg W may result in sudden death (Andrews 1965*b*). MacLaren *et al.* (1964) reported that an oral dose of 4–6 g Co may be toxic to store cattle, resulting in loss of appetite, general depression and death.

Copper

The concentration of Cu in pastures and other feeds is a poor indicator of their capacity to meet the Cu requirements of sheep and cattle. The reason for this is that other components, mainly Mo but also S (see p. 163), Zn, Fe (see p. 143), Cd, and organic constituents can affect the bioavailability of Cu (see Gawthorne 1987). These interactions are complex and not well enough defined to enable a reliable estimate of bioavailability to be made from the results of laboratory analyses.

Consequently, recommendations on dietary Cu requirements must be treated with caution. If it is suspected that the condition of flocks and herds is sub-optimal because of a Cu inadequacy, plasma Cu levels are a good guide to Cu reserves in the liver. However, production responses to Cu supplements are not widespread except where there is a sustained excess of Mo, and responses obtained could reflect a blocking of molybdenosis rather than indicating a need for Cu (Davies 1983; Phillippo 1983).

Cattle and sheep differ in their utilisation of Cu; sheep are more likely to suffer Cu toxicity because of greater retention of Cu in the liver (Howell 1996) whereas cattle are more likely to be Cu-deficient as a result of faster bilary excretion of Cu (Gooneratne *et al.* 1989).

Factorial estimation of requirements

There is a lack of quantitative information on the maintenance and production components of requirements, and what there is comes mainly from the UK, Europe and NZ where breeds and their nutritional environments are different from those common in Australia. There is, for example, substantial genetic variation in Cu metabolism between breeds of sheep (Wiener and Woolliams 1983) and within the Merino breed (Judson *et al.* 1994). Phenotypic differences have been observed between flocks within one breed (Knowles *et al.* 1998). Nevertheless, the information offers a guide to the magnitude of Cu requirements for maintenance, production and reproduction. In order to maintain steady-state concentrations of Cu in its tissues an animal needs to replace the endogenous losses that occur in urine, faeces and skin. Lee *et al.* (2002) have presented a generalised factorial model for the metabolism of Cu in a sheep. Animals that are growing muscle and bone, or are producing wool, milk or offspring, require larger amounts of Cu to provide for the accretion in these tissues and Grace and Lee (1990) have shown that Ca, P and Mg concentrations in bone are markedly increased by increasing Cu intake, even beyond the usually recommended levels.

Maintenance

The daily endogenous urinary and faecal Cu losses of mature ewes have been estimated as respectively 1 μg/kg W and 3 μg/kg W (Suttle 1974). The faecal loss is composed of Cu from

mucosal cells sloughed from the intestines, and Cu in secretions such as saliva, bile and gastric juice that has not been re-absorbed. The loss of Cu from the skin and its secretions is included in the Cu content of wool because it is impractical to separate physically the maintenance and production components.

The daily maintenance requirement for sheep, the sum of the above, totals 4 μg Cu/kg W. This is **adopted** here, although the level is uncertain because the endogenous losses increase with Cu intake and with hepatic Cu reserves (McDonald *et al.* 1979; Suttle 1983*a*). Underwood and Suttle (1999) indicate that the same value should be used for cattle.

Growth

Appropriate estimates are those of Suttle (1987*a*), who reported 0.5 mg Cu/kg LWG. The content does increase with increasing Cu intake (Suttle 1983*a*; Langlands *et al.* 1984).

Wool growth

Care must be exercised in sampling wool to avoid contamination from soil, cutting implements and sample containers. Clean wool usually contains approximately 4 mg Cu/kg (Underwood and Suttle 1999). Thus daily requirements will be greater in the Merino than in other breeds that produce less wool.

Pregnancy

The foetus, like the adult, requires Cu for the activity of essential Cu-dependent enzymes. Copper is accumulated in the liver and kidney, and in the placenta and other products of conception. For sheep, the ARC (1980) estimates are based on the data of Moss *et al.* (1974) that suggest an accumulation in the conceptus of 15, 85 and 186 μg Cu/d for the three trimesters of pregnancy. The total Cu content of the conceptus at birth has been measured at 20–30 mg (Williams *et al.* 1978). The accumulation of Cu in colostrum puts an added demand on the requirement of ewes, adding approximately 0.3 mg Cu/d during the last four days of pregnancy (Suttle 1987*a*).

For cattle, Cu requirements in pregnancy have been estimated by the ARC (1980) using a combination of direct and indirect measurements and are still the best available. In general, the content of the conceptus increases from 0.6 mg Cu/d in the first trimester to 1.6 mg Cu/d and 2.0 mg Cu/d in the last two trimesters. At birth the conceptus contains approximately 180 mg Cu.

Lactation

The Cu concentration in milk is in the vicinity of 0.22 mg Cu/l for ewes and 0.1 mg Cu/l for cows.

From the above estimates, the total net requirements for sheep and cattle at significant stages of physiological development can be computed as in Table 3.6.

Dietary requirements

Much uncertainty arises when attempts are made to convert total net requirements to dietary requirements because the coefficient of absorption may vary within a six-fold range (0.01–0.06). The dietary concentrations of S and of Mo are the main sources of variation within, as well as between, feeds. The Cu status of sheep is decreased by increases in dietary S, but there

Table 3.6. Net and gross Cu requirements of sheep and cattle

	Live weight (W) (kg)	Gain in W (kg/d)	Wool (g/d)	Milk (kg/d)	DM intake[A] (kg/d)	Net requirements[B] (mg/d)	Gross requirements					
							$A^C = 0.06$		$A^C = 0.03$		$A^C = 0.015$	
							mg/d	mg/kg DM	mg/d	mg/kg DM	mg/d	mg/kg DM
Sheep												
1 year-old	40	0.1	12	–	1.4	0.27	4.5	3.2	9.0	6.4	18.0	12.8
Ewe	50	–	12	–	1.0	0.25	4.2	4.2	8.4	8.4	16.8	16.8
Pregnant[D]												
Single	50	–	7	–	1.0	0.41	6.8	6.8	13.6	13.6	27.2	27.2
Twins	50	–	7	–	1.2	0.49	8.2	6.8	16.4	13.6	32.8	27.2
Lactating	50	–	7	1.5	1.8	0.56	9.3	5.2	18.6	10.4	37.2	20.8
Cattle												
Calf	200	0.7	–	–	6.0	1.15	19	3.2	38	6.4	76	12.8
Cow	500	–	–	–	10.0	2.00	33	3.3	67	6.7	133	13.3
Pregnant	500	–	–	–	10.0	4.00	66	6.7	132	13.4	264	26.8
Lactating	500	–	–	30.0	18.0	5.00	83	4.6	166	9.2	332	18.4

[A] DM digestibility 0.72 assumed.

[B] Components of net requirements: maintenance = 4 µg/kg W; weight gain = 0.5 mg/kg gain; wool = 4 mg/g clean wool growth; milk = 0.22 mg/l for sheep, 0.1 mg/l for cow; conceptus 0.14–0.22 mg Cu/d in ewe, 2 mg/d in cow.

[C] Cu absorbability [see text].

[D] Third trimester.

is some evidence (Simpson *et al.* 1981) that a similar change does not occur in cattle unless accompanied by increases in dietary Mo.

Suttle and McLauchlan (1976), using semi-purified diets, derived an equation describing the decrease in the Cu absorption coefficient with increasing S content of the diet and the further effect of the interaction between S and increasing Mo. The equation, shown graphically by the ARC (1980) and Suttle (1986), has been useful as an indicator of the possible magnitude of the effect that S and Mo have on Cu absorption, but it has since become apparent that it is not universal and cannot be applied with certainty to pastures or other feeds (Langlands *et al.* 1981; Suttle 1983*b*). It is therefore unreliable as an indication of the extent to which a given diet will satisfy Cu requirements.

There is seasonal variation in the availability of Cu from pastures. As a general rule it is less available from the lush green feed in winter and spring in the Mediterranean climate of southern Australia, and after the summer rainfalls of the north, than from dry feed. This difference probably reflects the higher protein and therefore S content of young herbage and, to an extent varying with location, a higher Mo content. Cyclic changes in blood Cu concentrations and liver Cu reserves in sheep and cattle are normal; in the Mediterranean region they decrease during winter and spring, and increase during summer and autumn. In Table 3.6, a range of absorption coefficients has been used to convert net Cu requirements to dietary Cu requirements. The latter requirements would be increased by up to about 50% during a period of new growth of pasture to allow for decreasing Cu availability, if it were thought to be desirable that body Cu status should not decline during that period. Underwood and Suttle (1999) suggest, as a general guideline, that the absorbability of Cu will be approximately 0.06 for a diet of roughage plus concentrates, 0.03 for normal green pasture, 0.015 for swards with >2 mg Mo/kg DM, 0.02 for swards with >800 mg Fe/kg DM and 0.04 for dead pasture.

Provided that the S concentrations in pasture DM are in the range of 1–3 g/kg and the Mo concentrations are in the range of 0.5–2.0 mg/kg, both cattle and sheep will maintain normal health and production despite fluctuation in their Cu reserves. With other minerals that can affect the metabolism, there can be cause for concern about Cu status if concentrations per kg DM exceed 100 mg Zn, 500 mg Fe or 5 mg Cd, which are all substantially greater than normally occur in pastures. The ultimate test of whether or not a given pasture or diet is satisfying the Cu requirement is the animal itself. If there are reasons to suspect that the Cu status of animals is not optimal, confirmation should be sought via analysis of blood and/or liver from post-mortem or biopsy samples.

Assessing copper status

The signs of Cu deficiency are well known. In sheep one of the first indicators is the loss of pigmentation in black wool, followed by loss of crimp (steely wool). In cattle, pigmentation of hair is reduced. Neonatal ataxia ('swayback') occurs in lambs from ewes with low Cu status (but is rare in calves), there is decreased growth rate, fragility of the long bones, diarrhoea in cattle and a hypochromic and macrocytic anaemia in both species (Underwood 1977).

Except for some areas in the western districts of Victoria and in south Gippsland (high Mo and S), parts of the calcareous littoral of South Australia (low availability of soil Cu), coastal sands of Western Australia, and coastal areas in Queensland and NSW (low soil Cu), rarely do unambiguous signs of deficiency appear. It is therefore essential that diagnoses be confirmed or

denied by the results of laboratory analyses of liver samples (biopsy or post-mortem) and/or analyses of Cu or Cu-dependent enzymes in blood.

Table 3.7 presents marginal bands for Cu concentrations in the diet, blood plasma and liver as aids for diagnosis of deficiency in ruminants on diets based on fresh herbage (H) or other roughage (R).

Table 3.7. Marginal bands[A] for Cu concentrations in the diet, liver and blood plasma (from Underwood and Suttle 1999)

Criterion	Diet[B]	Sheep and cattle	Deer and goats	Interpretive limits
Diet Cu (mg/kg DM)	H	6–8	6–8	Diet Mo <1.5 mg/kg DM
	R	4–6	4–6	Diet Mo <1.5 mg/kg DM
Liver Cu (μmol/kg DM)[CD]		100–300	122–244	
Plasma Cu (μmol/l)[D]		3–9	3–9	Diet Mo <15 mg/kg DM for cattle; <8 for others

[A] Values below the band indicate high probability of dysfunction; values above the band indicate minimal likelihood of Cu supplementation being beneficial.
[B] Diets of fresh herbage (H) or other roughage (R).
[C] Divide by 3.0 to obtain values on a fresh weight basis.
[D] Multiply by 0.064 to obtain values in mg/kg or mg/l.

An indication of interference by high concentrations of Mo with Cu availability in the early stages may be obtained by measuring the plasma Cu concentration before and after precipitation of plasma proteins in 5% trichloroacetic acid (TCA). When the TCA-soluble Cu concentration is expressed as a proportion of the total plasma Cu concentration a value significantly less than 1.0 is putative evidence of interference by Mo in the normal forms of plasma Cu (Allen 1986; Yuan *et al.* 1988).

If diagnostic tests indicate a low Cu status, then pasture mineral tests are useful in determining if the deficiency is a simple or induced Cu deficiency. This will determine the most appropriate method of preventing and correcting the deficiency. If the deficiency is simple, then Cu application to the soil may be the most economical means of correction since the applied Cu is not readily leached from the soil and may persist for >20 years. If it is an induced deficiency, then treatment of the animal, as outlined in the following section, is usually recommended.

Copper supplementation

Drenching with copper sulfate is not recommended because of the ineffectiveness of Cu dispensed in the rumen and also the risk of toxicity. The preferred methods of Cu supplementation are (*a*) with particles of CuO (prepared by heating copper wire to give a uniform oxide coating on a Cu core) administered in a gelatinous capsule: 2.5 g for sheep; 10–40 g for cattle or (*b*) by subcutaneous injection of copper glycinate. Either method is effective for 6–12 months (see Judson (1996) for a comparison of procedures).

Copper toxicity

Chronic toxicity is more common than the acute form, and sheep, rather than cattle, succumb to this problem in practice. For the diagnosis of chronic copper poisoning, Underwood and

Suttle (1999) suggest that marginal bands for Cu concentration (mg/kg DM) in the diet are 12–36 for sheep, 100–300 for cattle and 30–100 for goats. Poisoning is usually encountered in two circumstances: in housed sheep or in sheep grazing plants containing pyrrolizidine alkaloids.

When sheep are housed and fed dry feeds, including concentrates, Cu tends to accumulate in the liver. This is because these feeds have a relatively high availability of Cu and relatively low levels of Mo and S. Copper concentrations as low as 10 mg/kg DM in mixed hay and concentrate diets can be dangerous (K. G. Hogan *et al.* 1968; Buck 1970). The situation is exacerbated if animals have access to mineral mixes containing high concentrations of Cu, or if they are given drenches containing Cu. Underwood and Suttle (1999) indicate marginal bands of 6.4–16.0 mmol/kg DM for liver Cu and 20–25 μmol/l for plasma Cu in sheep, cattle and goats. Values above these bands strongly suggest chronic Cu poisoning.

Long-term ingestion of *Heliotropium*, *Echium* (e.g. Paterson's curse), or *Senecio* (e.g. ragwort) spp. that contain pyrrolizidine alkaloids has been associated with chronic Cu toxicity in parts of New South Wales and Victoria. Damage to the liver caused by the alkaloids apparently increases the tendency of Cu to accumulate in that organ. Long-term ingestion of pastures in which subterranean clover is dominant, with 10–15 mg Cu/kg DM and less than 0.2 mg Mo/kg DM but no alkaloids, can also lead to a risk of toxicity (Howell and Gooneratne 1987). Accumulation of Cu in the liver over several months in both of the above circumstances can result in concentrations in excess of 2000 mg Cu/kg DM in liver, and 200 mg Cu/kg DM in kidney. The episodic release of Cu from the liver into the bloodstream causes haemolysis, haemoglobinuria, jaundice and eventual death.

Acute Cu toxicity is uncommon, and generally arises as a result of human error in providing Cu supplementation. The acute dietary doses are 20–50 mg Cu/kg DM for lambs, 130 mg Cu/kg DM for adult sheep, and 200 mg Cu/kg DM for adult cattle (Howell and Gooneratne 1987). There have been many instances where sheep and cattle have died as a result of overdosing with Cu supplements such as CuCa-EDTA or $CuSO_4$. Single doses of more than 50 mg for sheep, 100 mg for calves, or 200 mg for adult cattle can be expected to be toxic (Howell and Gooneratne 1987). Diethylamino cupro-oxyquinoline sulfonate was withdrawn from the market as an injectable supplement because of the high risk of toxicity.

Iodine

Iodine is a constituent of the thyroid hormones thyroxine (T4) and tri-iodothyronine (T3). Areas of south-eastern Australia were once noted for endemic goitre in humans caused by I deficiency. Iodine nutrition did not then seem to be limiting for grazing ruminants; Dawbarn and Farr (1932), for example, concluded that the thyroid I contents in adult sheep in the eastern States and South Australia were not low enough (less than 1 g I/kg dry weight) to suggest the possibility of deficiency. Nevertheless, the occurrence of goitre in newborn lambs and kids in some areas of those States, and Tasmania but apparently not Western Australia (Statham and Bray 1975; King 1976; Plant 1976; Caple *et al.* 1980), and increased lamb birth weight, survival and growth rate following I supplementation of pregnant ewes (Knights *et al.* 1979; Ellis and Coverdale 1982) indicate that I nutrition can be limiting for health and production in a number of localities under particular environmental conditions (Hosking *et al.* 1986). In addition, there is evidence of variation in susceptibility to goitre between breeds; for example, George *et al.*

(1966) reported a higher incidence in Dorset Horn and Border Leicester × Merino lambs than in Merino lambs.

Production of foetal thyroid hormones is controlled by the pituitary–thyroid axis (Hopkins 1975) and is independent of maternal thyroid hormones. Synthesis in the foetus depends on the transfer of I across the placenta by an active transport system, but the I in the thyroid gland of the dam is not directly available. A low I intake, which may not cause deficiency in pregnant ewes with adequate thyroid I stores, could result in insufficient placental transfer of I for foetal thyroid function, and lead to low survival of hypothyroid lambs. Diets providing less than 0.2 mg/d to pregnant ewes have produced goitre in lambs (Mason 1976).

The foetus is most sensitive to I deficiency during the last three months of gestation when the growth and development of the brain, the lungs and heart, bone, and wool follicles depend on the foetal thyroid hormones. These hormones, together with cortisol, stimulate cells lining the alveoli in the lungs to produce surfactant that is necessary for lung maturation and insufflation after birth.

Extreme deficiency results in decreased thyroid hormone production. A negative feedback system interacting at the hypothalamus results in increased secretion of thyrotropin-releasing factor (TRF), which stimulates secretion of thyroid-stimulating hormone (TSH) from the anterior pituitary gland. Continued secretion of TSH results in increased size of the thyroid gland and goitre. Iodine deficiency also results in increased susceptibility of newborn animals to cold. Thyroid hormones interact with the adrenal catecholamines in stimulating catabolism of brown fat and non-shivering thermogenesis in cold-stressed neonates (Caple and Nugent 1982). In adult animals, thyroid hormones are involved in changes with ambient temperature in the rate of passage of digesta and feed digestibility (Kennedy *et al.* 1977) as well as affecting energy metabolism.

There is an interaction between I nutrition and Se nutrition mediated through the Se-containing enzyme, type 3 iodothyronine deiodinase, that catalyses the conversion of T4 to the metabolically active T3 and to inactive metabolites (Berry *et al.* 1991). The enzyme activity in the placenta may regulate thyroid hormone inactivation during embryological development (Salvatore *et al.* 1995), and its activity in many tissues can be influenced by Se nutrition (Arthur *et al.* 1988*a*; Beckett *et al.* 1989). Selenium deficiency has been shown to compound the adverse effects of I deficiency (Arthur 1992). Combined deficiencies of I and Se are likely to increase the risks of neonatal mortality in lambs and kids.

Requirements

The rumen is the principal site of I absorption. There is an endogenous secretion of I into the abomasum but the majority is reabsorbed in the intestines and little is lost in faeces (Underwood 1977).

Smith (1980) has demonstrated that a significant relationship exists between the logarithm of the adult body weight and the maintenance I requirement of a number of species:

$$\text{Requirement } (\mu\text{g I/kg W}) = 1.36 - 0.16 \log_{10} \text{W}$$

The ARC (1980) considered that diets containing 0.5 mg I/kg DM are adequate for all classes of cattle and sheep, provided goitrogens are absent. This estimate is **adopted** here for general use, but the requirement may be lower during summer. Thyroid hormone secretion rate tends to be inversely related to ambient temperature and the ARC (1980) suggested 0.15 mg I/kg DM may

be adequate during summer for adult cattle and sheep, including those lactating.

The dietary requirement is influenced by the presence of goitrogenic substances in the feed. These are of two main types. The cyanogenic goitrogens, such as thiocyanate derived from the cyanide in white clover and the glucosinolates in some brassica crops, impair I uptake by the thyroid, and their effects can be overcome by I supplementation (Barry 1983). The thiouracil-type goitrogens, found in brassica seeds, inhibit iodination of tyrosine residues within the gland, and their effects are much less susceptible to reversal by supplementation. The consequent increases in I requirements have not been defined but the ARC (1980) suggests that the dietary content should be increased to 2 mg I/kg DM when substantial quantities of goitrogens are present.

Hypothyroidism also occurs in cattle grazing *Leueaena leucocephala* because they do not have a ruminal microflora capable of degrading a goitrogenic metabolite of the mimosine in this forage (Jones and Hegarty 1984; Jones and Jones 1984).

Signs of deficiency and status

The presence of enlarged thyroid glands in newborn animals, particularly in association with high mortality, provides an indication of I deficiency. Goitre and hypothyroidism due to I deficiency alone, or in combination with goitrogens, causes sporadic losses of newborn lambs in Tasmania (Statham and Bray 1975), New South Wales (Setchell *et al.* 1960), and in Victoria (Caple *et al.* 1980). Goats appear more susceptible to I deficiency than sheep under pastoral conditions in south-eastern Australia, and abortions, hairless, and stillborn goitrous kids occur in affected herds (Caple *et al.* 1985).

Thyroid enlargement is very often difficult to detect without detailed examination and is easily overlooked, but is indicated by a ratio of thyroid weight to body weight greater than 0.4 g/kg.

Various indicators may be used to assess I status including concentrations in diet, blood, urine and milk; thyroid weight, histology and I content in newborn animals; and thyroid function tests involving measurement of thyroid hormone concentrations in plasma.

Milk

The average daily I intake of a dairy herd (y, mg/cow) can be estimated from the I content (x, μg/l) of bulk milk with the relationship derived by Alderman and Stranks (1967):

$$y = 0.37x + 0.05$$

Concentrations less than about 25 μg/l indicate inadequate intake. Mason (1976) has reported relationships of similar form for lactating ewes. The thyroid hormone secretion rate increases during lactation in both cattle and sheep, but the quantitative importance of I losses in milk appears to differ between the species. The dietary I requirement of a 500 kg cow for thyroid hormone secretion (y, mg/day) was related to butterfat production (x, kg/day) by the equation (Sorensen 1958):

$$y = 7.9x + 0.07$$

At milk yields of 10–25 l/d containing 40 g fat/l, the I output in milk was estimated to be between 0.03 and 0.06 of the dietary intake required to maintain thyroid activity. Thus milk I losses in cows are insignificant compared with the demand for thyroid hormone secretion (ARC 1980). In contrast, lactating ewes fed on rations marginal in I showed a high fractional uptake of I by the mammary gland at the expense of a fall in the proportion of circulating I taken up by the

thyroid gland (Falconer 1963). Losses of I in milk of ewes yielding 0.5–1.0 l/day may represent up to 0.5 of the dietary requirement for thyroid hormone secretion, and can be a substantial proportion of the animal's I turnover (ARC 1980).

Lactating ewes secrete approximately 0.4 of ingested I in their milk (Miller *et al.* 1975). It has been observed that where newborn lambs had histological changes in the thyroid indicative of deficiency, ewes had milk I concentrations of less than 80 μg/l (Mason 1976) and similar values for milk I concentrations in does have been associated with goitre and hypothyroidism in newborn kids (Caple *et al.* 1985). However, Grace *et al.* (2001) have found that goitre in lambs is associated with ewes with serum I <30 μg/l and milk I <26 μg/l.

Thyroid function tests

Thyroid function can be assessed from the concentrations of free or total thyroxine (T4) or triiodothyronine (T3) in plasma. To confirm that suspected hypothyroidism is due to I deficiency it is necessary to demonstrate an increase in plasma thyroid hormone concentrations after I supplementation. Recent work suggests that plasma inorganic I levels are more reliable than plasma T3 and T4 levels (Grace *et al.* 2001).

Wallace *et al.* (1978) found that low plasma thyroxine concentrations (less than 40 μg/1) in lactating ewes were correlated with areas where goitre had occurred. However, Caple *et al.* (1985) found that the concentrations in adult ruminants provided no indication of extreme or marginal I deficiencies in flocks or herds. There is a seasonal variation in plasma thyroxine concentrations, with minimum values occurring in early autumn and maximum values occurring during winter (Sutherland and Irvine 1974; Andrewartha *et al.* 1980). Where ewes or does have adequate I nutrition during pregnancy, the newborn lambs and kids have higher plasma thyroxine concentrations than their mothers. Because lambs and kids with goitre have lower concentrations than their mothers, a comparison with concentrations in their mothers enables hypothyroidism and inadequate I nutrition to be detected. The age of the lamb or kid needs to be considered in the interpretation. Plasma thyroxine concentrations normally decrease after birth, and by eight weeks the levels are similar in the lambs and ewes, or kids and does (Andrewartha *et al.* 1980; Caple *et al.* 1985). The plasma thyroid hormone concentrations in I-deficient lambs and kids increase within hours following supplementation.

Season and plant species

A marked seasonal variation in the I nutrition of grazing cattle and sheep has been demonstrated in Victoria by monitoring milk I concentrations (Hubble 1981; Azuolas and Caple 1984). Soil ingestion has been assumed to be an important factor in determining the I intake of grazing sheep because soil has a higher content than herbage (Healy *et al.* 1972). Iodine is apparently not required by plants and uptake depends more on the species of plants present than on the effects of season (Johnson and Butler 1957). Plant I concentrations in the range of 0.09–5.00 mg/kg DM have been reported (Little 1982) and in a number of instances would provide less than even the reduced requirements of animals in summer.

The I intake of grazing cows, ewes, and does in Victoria, as assessed from changes in milk concentrations, increases during late spring, reaches a maximum during the summer months, and declines very rapidly within days after the autumn rains. It decreases further during winter and early spring. This seasonal pattern may be due to leaching or upward movement of I in

the soil in response to changes in rainfall and temperature, and to variation in soil ingestion. In Victoria, only lambs and kids born between August and October are generally susceptible to deficiency (Caple *et al.* 1982). Goats appear more susceptible than other grazing ruminants. Foetal goats undergo most rapid development during winter and spring when I intake by does is lowest (Caple *et al.* 1985).

Iodine supplementation

Deficiency can be prevented by provision of iodised salt licks containing 25 g potassium iodate/100 kg salt. Other suitable I sources include calcium iodate and pentacalcium orthoperiodate. Potassium iodide is unsuitable because it suffers extensive loss of I by oxidation and volatilisation or by leaching.

Deficiency in lambs can be prevented by drenching the ewe once during the third and fourth month of pregnancy with 280 mg of potassium iodide. Iodine may be administered by intramuscular injection as iodised poppyseed oil, which contains 40% iodine. Ewes treated with 1 ml had higher milk I concentrations than untreated ewes 16 months later, and after the ewes had gone through two pregnancies (Azuolas and Caple 1984). Statham and Koen (1982) reported that this treatment of ewes controlled goitre in lambs, as assessed by histological examination of lamb thyroid from two pregnancies in two years.

In Victoria it is recommended that all breeding goats should be provided with supplemental I, for example, by strategic drenching or iodised salt licks, to prevent goitre and heavy mortality in newborn kids. In severely deficient areas, iodised oil injections (1 ml) are recommended for pregnant does each year (Hosking *et al.* 1986).

Iodine excess

Excessively high I intakes can result in iodism, and it is recommended that diets should not contain more than 8 mg I/kg DM (ARC 1980). Calves fed diets containing more than 50 mg I/kg DM, which is the NRC (1980) 'maximum tolerable level', had reduced feed intakes and weight gains, began coughing, and had a profuse nasal discharge (Underwood 1977).

Because of concern that excessive use of iodophors in dairy sanitation and mastitis prevention may lead to high concentration of I in milk, dairy practice in Australia has moved to other sanitising agents. The Food Standards Code of the National Health and Medical Research Council of Australia (NHMRC) stipulates that concentrations in milk from dairy cows must not exceed 500 μg I/1 (3.9 μmol I/1), and will generally not be exceeded if iodophors etc. are used with care.

Iron

Sheep and cattle, like other mammals, contain 50–70 mg Fe/kg W of which more than half is present in haemoglobin. There is substantial recycling within the body, for example in red blood cell turnover. There have been no reports of a simple deficiency in grazing animals, though if they suffer a chronic loss of blood such as from endo- or ecto-parasitism (e.g. haemonchosis, lice, ticks) they may develop an Fe-deficiency anaemia (Kaneko 1980).

Iron requirements are agreed by several reports (ARC 1980; Towers and Grace 1983*a*; Anon. 1984; Grace 1986) to be 30–40 mg Fe/kg DM, the higher value applying to calves of less than 150 kg W and to pregnant and lactating cows and ewes. All solid feeds, except dried milk, usually contain more than those amounts of Fe, and concentrations in grazed pasture can be much

higher because of contamination with soil (Fleming 1965). The Fe in some water supplies, alone, can more than meet requirements.

Ling *et al.* (1961) reported that cow's milk contains 0.15–0.67 mg Fe/kg; the mean concentration in 24 samples of ewe's milk obtained early in lactation by Ashton and Yousef (1966) was 0.77 mg Fe/kg. On a DM basis these concentrations do not exceed about one-tenth of those desirable, and it is evident that calves and lambs reared on milk or milk products, without access to solid feed and without an Fe supplement, could deplete their stores available at birth and become Fe deficient. Although Webster *et al.* (1975*b*) found that energy retention and growth by calves given 20 mg Fe/kg DM were not impaired compared with 40 or 100 mg Fe/kg DM, the mean haemoglobin concentration of 71 g/l was less than with the higher Fe intake, where concentrations were approximately in the normal range of 110–140 g/1. The lower level would usually be taken to indicate anaemia. With lambs, Lawlor *et al.* (1965) found that 25 mg Fe/kg DM did not support maximum growth and that the minimum requirement was not more than 40 mg Fe/kg DM. Bremner *et al.* (1976) reported that the first measurable response by both calves and lambs to induced anaemia was a fall in appetite and that this was a reliable indication of the onset of the condition.

In these studies the Fe was provided in soluble, readily available forms such as the sulfate, chloride or citrate; the availability of Fe from Fe_2O_3 appears to be very low, or nil (Ammerman *et al.* 1995). It is recommended that milk or milk-product diets for calves and lambs should contain not less than 30 mg Fe/kg DM in soluble form. It has been suggested (Anon. 1984) that 80–100 mg Fe/kg DM may be necessary for calves of some breeds growing rapidly, but no supporting evidence was provided and it appears that Fe concentrations need not exceed 40 mg/kg DM.

The NRC (1980) maximum tolerable limits are 1000 and 500 mg Fe/kg DM for respectively cattle and sheep, but the ARC (1980) proposes the lower value for both species. Higher intakes by grazing animals will sometimes be inevitable because of soil contamination in their feed. Soil Fe is likely to be less available than that in the supplements used to study Fe toleration and toxicity, but it can adversely affect the availability of Cu in forage. In studies by Humphries *et al.* (1983) with weaned calves, initially about four-months old and 140 kg W and given a roughage plus grain diet, the addition of 800 mg Fe/kg DM had the same effect on all indices of Cu status as 5 mg Mo/kg DM. They quote other work that indicated 250 mg Fe/kg DM was sufficient to reduce hepatic Cu reserves in calves. These effects occurred without any reduction in feed intake, which is one result of excess Fe, and the mechanisms that disturb Cu metabolism have not been defined.

It is suggested that when Fe intake can be controlled it should not exceed 500 mg/kg DM for all ruminants; it may be advisable to set a limit at about half that concentration for liquid milk diets. With grazing animals, when Fe intakes cannot be controlled, the implications for Cu status are considered in *Copper* (see p. 137).

Magnesium

Magnesium, the most abundant intracellular divalent cation, is a cofactor for many enzymes involved in oxidative phosphorylation and the metabolism of carbohydrates, lipids, proteins and nucleic acids. About 70% of body Mg is associated with the skeleton, 25% with the skeletal muscle mass, and 1% with the extracellular space (Grace 1981). A kilogram gain in bodyweight

is associated with 10.7–12.3 mmol (0.26–0.3 g) of Mg in sheep and 18.5 mmol (0.45 g) in cattle, while 1 kg of wool contains about 11.5 mmol (0.28 g) of Mg (Rook and Storry 1962).

Extracellular Mg has an important role in the moderation of nerve impulses and neuromuscular transmission. The normal plasma concentration ranges between 0.75 and 1.3 mmol Mg/l (18.2–31.6 mg/1). A decrease can result in a reduction in the concentration of Mg in the cerebrospinal fluid to below 0.5 mmol/l (12.2 mg/l) and lead to hyperexcitability, muscular spasms, convulsions and death from hypomagnesaemic tetany. This disorder affects lactating dairy and beef cows and, rarely, ewes grazing grass pastures in autumn and winter in southern Australia (Herd 1965; Herd *et al.* 1965).

Absorption

Magnesium is absorbed very efficiently (0.9) from milk by young calves and lambs (ARC 1980). The coefficient of absorption decreases rapidly with age and, in calves fed milk on fibrous bedding, the values decrease to 0.12 at 14 weeks of age. In young ruminants, Mg is absorbed from the small intestine, whereas in adult ruminants the small intestine is a site of net secretion. The rumen becomes the major site of absorption once it develops, the large intestine also being a site of net absorption though of lesser importance (Grace *et al.* 1974). Dua and Care (1995) have reviewed the factors affecting Mg absorption in ruminants.

Absorption from the rumen is by an active transport process and is unaffected by plasma Mg concentrations (Martens and Stossel 1988). In adult sheep the apparent absorption of Mg increases from about 0.1–0.6 on forage diets as forage K falls from about 50–10 g/kg DM. High soil K interferes with Mg absorption by plants and also Mg absorption from the rumen (Tomas and Potter 1976; Martens *et al.* 1987; Grace *et al.* 1988). In cattle, absorbablity increases from 0.1 to only 0.2 in the same conditions; lower absorbability of Mg in cattle may account for their greater susceptibility than sheep to Mg-deficiency conditions. The urinary endogenous loss is negligible in animals on low Mg intakes, and when plasma Mg decreases below the renal threshold. The daily faecal endogenous loss for both sheep and cattle is taken as 3 mg/kg W by the ARC (1980). Most of this is from the small intestine where net secretion shows wide variation and is positively correlated with plasma Mg concentration (Martens 1981; Martens and Stossel 1988).

Magnesium absorbed in excess of requirements is excreted in the urine. Low serum concentrations in dairy cows, less than 0.65 mmol Mg/1 (15.8 mg/1), occur only when the urinary excretion is less than 1 g Mg/d (Kemp 1983). As a cow in Mg balance will excrete 2.5 g Mg/d, measurement of urinary excretion is considered a better measure to obtain information on the Mg status and supply to cattle than the concentration in blood plasma or serum (Kemp 1983; Caple and Halpin 1985). For practical purposes, single urine samples can be used and the variation in water excretion can be allowed for by dividing the urine Mg concentration by urine solute concentration (osmolality) or creatinine concentration. Urine Mg values greater than 2 μmol Mg/mosmole or 1.5 mmol Mg/mmol creatinine indicate adequate Mg status in cattle (Caple and Halpin 1985).

The continual absorption by a saturable, energy-dependent process from the reticulorumen is crucial for the homeostatic control of Mg metabolism in sheep (Martens 1983). The main controlling factors appear to be the Mg concentration in the liquid phase of the digesta, and changes in the rate of Mg transport through the rumen wall caused by factors such as dietary

constituents, for example K (Tomas and Potter 1976) and Na (Martens *et al.* 1987). Increased K concentrations in the reticulorumen reduce the absorptive flux (Grace *et al.* 1988) by increasing the transcellular potential difference across the rumen wall (Martens *et al.* 1987). High intraruminal ammonium ion concentrations (30–70 mmol/l) also reduce Mg absorption, and the effect appears to be additive and independent of that of K (Care *et al.* 1984), but binding of Mg to organic moieties in the rumen contents is unlikely to be important (Grace *et al.* 1988). Lush, high-protein herbage of high K and low Na content will thus result in reduced Mg absorption from the rumen.

The coefficient of absorption of Mg is high in lambs and calves soon after birth and a mean value of 0.7 is suggested for the first few weeks on a milk diet. Absorption falls steeply after weaning and, on normal pasture diets, mean values of 0.25 for adult sheep and 0.15 for adult cattle are suggested.

Table 3.8. The amounts of Mg associated with the endogenous loss, growth, pregnancy and lactation in sheep and cattle

		Sheep	Cattle
Endogenous loss (mg Mg/kg W)		3	3
Growth (g Mg/kg gain)		0.41	0.45
Lactation (g Mg/kg milk)		0.17	0.12
Pregnancy (increment g/d):			
	early	0.01	0.12
	mid	0.03	0.21
	late	0.05	0.33

Requirements

Using net requirements (Table 3.8) for maintenance, growth, pregnancy and lactation of sheep and cattle derived by factorial estimates (ARC 1980; Grace 1983*a*) and the above estimates of absorption, the dietary requirements for Mg shown in Table 3.9 have been adapted from Underwood and Suttle (1999) and are **adopted** here.

Table 3.9. Estimates of the mean dietary requirements for Mg by grazing sheep and cattle selecting a diet with about 30 g K/kg DM and a DM digestibility of about 0.75 (adapted from Underwood and Suttle 1999)

		Dietary requirement[A] (g Mg/kg DM)
Sheep		
Growth	0.1 kg/d	1.0
	0.2 kg/d	0.9
Pregnancy	Last 12 weeks	0.9
Milk yield	1–2 kg/d	1.2
Cattle		
Growth	0.5 kg/d	1.5
	1.0 kg/d	1.3
Pregnancy	Last 12 weeks	2.0
Milk yield	10 kg/d	2.2
	20 kg/d	2.0
	30 kg/d	1.9

[A] Dietary requirements for housed sheep and cattle are about 50% and 65%, respectively, of the values for grazing animals because of more efficient absorption of Mg from a diet of hay and concentrate.

Deficiency

Growth in young animals

Calves fed milk diets deficient in Mg for extended periods show poor growth, calcification of soft tissue, increased irritability, tetany and convulsions (Blaxter *et al.* 1954).

Weight gains by weaned lambs grazing winter wheat forage in south-east NSW have been markedly improved by Mg supplementation (Dove 2006), an increase attributed to high K levels in the forage and poor absorption of Mg from the soil due to its low pH and high K content.

Hypomagnesaemic tetany

Hypomagnesaemia (grass tetany) occurs in cattle grazing temperate pastures in south-eastern Australia (Herd *et al.* 1965), causing losses of 0.5% of cows in dairy herds (Allen and Caple 1980) and 0.3% in beef herds (Shiel *et al.* 1980; Harris *et al.* 1983). The disorder is more common where cattle graze mixed pastures containing less clover than grass, and where the herbage concentrations of Mg are less than 1 g/kg DM, Na less than 1.5 g/kg DM, and K greater than 30 g/kg DM (Metson *et al.* 1966; Jolley and Leaver 1974). It occurs more frequently where K and N fertilisers have been applied to pastures (Harris *et al.* 1983), or where soils are naturally high in K and low in Na (Jolley and Leaver 1974). Havilah *et al.* (2005) suggest that in these circumstances, the K balance of the diet should be tested. If the following ratio (with concentrations expressed as % diet DM) is greater than 2.2, then precautions against grass tetany are necessary.

$$\frac{\%\ potassium \times 256}{\%\ calcium \times 499 + \%\ magnesium \times 823}$$

This threshhold was exceeded in winter wheat forage grazed by lambs that showed a growth response to Mg (Dove 2006). The disorder is not found in cattle grazing tropical pastures, which generally have a higher Mg content than temperate pastures; in both instances, legumes generally contain more Mg than grasses (Norton 1982).

Hypomagnesaemic grass tetany in cattle is considered to be a complex disorder (Grace 1983*a*), but this may simply be due to the variety of circumstances that can lead to a reduction in Mg absorption, and a decrease in plasma and cerebrospinal fluid Mg concentrations. In beef herds in southern Australia there are several types of grass tetany syndromes that can be diagnosed according to the ages of cows affected, and the aetiological factors inducing the fatal nervous disorder. Cows older than six years are most commonly affected, particularly if they are overfat at calving and lose live weight during lactation. Younger, two- and three-year old cows may be affected in herds with the more complex types of syndromes associated with high K intake, and low Na and P nutrition.

The important aetiological factors in grass tetany include: (a) low Mg intake, which can arise simply through a reduction in feed intake when cows are grazing short grass-dominant pastures, and where pastures contain less than 1.5 g Mg/kg DM; (b) high K and low Na intakes, which have important implications for Mg absorption from the rumen. Soils naturally high in K or fertilised with potash, and low in Na are high-risk areas (Jolley and Leaver 1974); and (c) the cow's ability to maintain Ca homeostasis. Cows with hypomagnesaemia do not develop grass tetany until blood Ca levels decrease (Hemmingway and Ritchie 1965; Allcroft and Burns 1968). Hay feeding is an important control measure in herds where hypocalcaemia precipitates grass tetany in hypomagnesaemic cows. Phosphorus deficiency predisposes cows to hypocalcaemia,

and has been found to precipitate grass tetany in young cows. Other important factors in grass tetany include the body condition of older cows in a herd (Harris *et al.* 1983), grazing management and provision of shelter, and husbandry procedures that involve a reduction of food intake in high-risk cows.

In ewes, the incidence of grass tetany is generally low, perhaps because of greater Mg absorbability in sheep and occurs only in the presence of hypocalcaemia, but it can be a problem in older ewes rearing twin lambs (Treacher and Caja 2002), when the onset of tetany can be very sudden. Underwood and Suttle (1999) suggest that a flock may respond to Mg supplementation if the mean serum Mg concentration is less than 0.6 mmol/l.

There are several reasons why grass tetany continues to be a problem for the beef cattle industry in southern Australia. Most herds are grazed on improved pastures that contain mainly grass species during autumn and winter and which usually have lower Mg and Ca concentrations than leguminous pastures (Jolley and Leaver 1974). Cows in winter-rainfall areas are mated to calve in the autumn with the object of producing vealer calves to be finished on spring pastures. With this system, cows invariably become fat over spring and summer and, after calving in the autumn, lose body weight during lactation between May and September. It is not uncommon for older and fatter cows in herds to lose up to 1 kg W/d in this main risk period for grass tetany. The main loss of Mg in cows is via milk, and essentially no Mg is obtained from the tissues mobilised during loss of live weight to support lactation (ARC 1980). The selection of beef bulls on the growth rate of calves means that cows are being bred for high milk yields. Cows that maintain milk yield by losing live weight in early lactation are predisposed to hypomagnesaemic grass tetany if they do not receive additional Mg in the diet, or hay to prevent the weight loss.

Dairy cows in herds with mean blood Mg concentrations of less than 0.6 mmol/l have shown increases in milk production when supplemented with Mg (Turner and Neall 1978). Low plasma Mg concentrations in cows lead to a reduction in the amounts of Ca able to be mobilised in response to hypocalcaemia (Sansom *et al.* 1983), and may predispose milk fever in cows around parturition.

Cows fed restricted roughage and high-concentrate diets containing adequate Mg, with serum Mg greater than 0.8 mmol/l have shown up to 15% increases in milk fat production when Mg intake was increased by two to four times the recommended amount (Emery 1983).

Supplementation

Because there is no readily available store of Mg in the body, Mg supplements have to be given daily. Most Mg salts are quite unpalatable and an important practical aspect in feeding supplemental Mg is combining it with other palatable ingredients such as salt, molasses, concentrates and hay. There are several ways of providing Mg supplements for ruminants including individual drenching, treatment of hay, pasture topdressing, water-trough treatments, and licks (Grace 1983*a*). It is desirable that the supplement should be readily soluble in the rumen liquor and provide sufficient Mg to prevent the development of hypomagnesaemia in any individual animal in a herd.

Individual cows may be drenched daily with magnesium sulfate or chloride to provide 10 g Mg. Micronised (300 mesh) magnesium oxide can be suspended in water and administered by drenching guns provided it is constantly mixed to maintain the suspension. Magnesium oxide may also be added to hay at the rate of 50 g per cow daily.

Pastures may be dusted with calcined magnesite (60 mesh) or causmag (500 g/cow) just before grazing. One treatment at weekly intervals usually suffices, but if rainfall exceeds 40–50 mm within 2–3 days of dusting, a further application is required.

Addition of magnesium chloride or magnesium sulfate to water is usually an unreliable method of supplementing cows because their water intake is generally low when they are grazing lush tetany-prone pastures. Magnesium licks are considered unreliable because (see p. 228) the intake of some cows will be nil or small and licking may be intermittent (Grace 1983*a*).

An intraruminal device (Laby 1980) that releases about 1.5 g Mg/d for 90 days after a stabilising period of one week has been developed for Mg supplementation of cattle.

Excessive Mg intakes have been associated with diarrhoea in cattle, and dietary concentrations exceeding 13 g Mg/kg DM substantially reduce growth rates in calves. On concentrate diets, excessive Mg has caused urolithiasis in male sheep. Saul and Flinn (1985) found that saline drinking water containing 650 mg Mg/l had no effect on liveweight gain, feed intake or general health of young sheep or cattle. However, drinking water with 5000 and 11 000 ppm of total soluble salts reduced liveweight gain in young cattle (Chapter 5).

Manganese

Manganese deficiency has been produced in a number of animal species, including rats, guinea pigs, goats, sheep and cattle (see Underwood and Suttle 1999). In ruminants, deficiency causes skeletal abnormalities and lameness (Lassiter and Morton 1968; Rojas *et al.* 1965) and depressed reproductive performance (Rojas *et al.* 1965; Anke and Groppel 1970; Hidiroglou *et al.* 1978). In other animal species, deficiency has retarded growth (Paynter 1980*a*), caused neonatal ataxia (Erway *et al.* 1970), abnormal carbohydrate metabolism (Baly *et al.* 1984) and resulted in morphological and functional changes to the mitochondria (Hurley *et al.* 1970).

Manganese is a component or activator of numerous enzymes. For example, skeletal abnormalities and ataxia are probably the result of reduced synthesis of the sulfated mucopolysaccharides that make up the organic matrix of the bone (Everson 1970; Erway and Purichia 1974; Leach 1974) due to the role of Mn in the glycosyltransferase enzymes. Manganese deficiency causes a reduction in the activity of manganese superoxide dismutase (MnSOD) (Paynter 1980*a*; De Rosa *et al.* 1980). This enzyme is believed to function in the protection of cells from the toxic effects of free radicals, and low activities are associated with increases in *in vitro* peroxidation of mitochondrial fractions (Paynter 1980*b*). Because nutritional muscular dystrophy resulting from Se and vitamin E deficiency in ruminants is caused by uncontrolled peroxidation of tissues, it is possible that Mn intake, through changes in the activity of MnSOD, may influence the susceptibility of ruminants to this disorder (Paynter and Caple 1984; Masters and Paynter 1988). Manganese is also a component of a number of other enzymes such as the gluconeogenic enzyme pyruvate carboxylase and is required for the activity of the urea-cycle enzyme arginase. Neither of these two enzymes appear to become limiting during Mn deficiency.

Absorption and storage

Manganese is not well absorbed, and over a wide range of intakes in cattle the absorption was only 0.005–0.010 (Sansom *et al.* 1978). In other experiments with sheep, apparent absorptions ranging from 0.07–0.14 have been reported (Grace 1975; Ivan *et al.* 1983). Most of the absorbed Mn is removed from the portal blood in the liver and excreted in the bile (Sansom *et al.* 1978) and subsequently in faeces. Less than 0.01 of the ingested Mn is excreted in the urine with the

rest in the faeces (Grace 1975; Ivan *et al.* 1983). It has been reported (Grace 1983*b*) that the body of a 50 kg sheep contains approximately 40 mg Mn, and that almost half of this is in wool fibre so that the fleece-free body contains approximately 21 mg. Much of this is found in the digestive tract (8.5 mg) and the skin (5 mg). Liver and bone also contain substantial amounts, and the 0.1 of body Mn in the liver is labile and may act as a store that is depleted during a deficiency (Lassiter and Morton 1968).

There are no biochemical criteria to readily assess Mn status in animals. Plasma contains low concentrations (1.0–4.0 μg Mn/l) and this changes little with different intakes (Masters *et al.* 1988). The amount in wool has been reported to decrease during deficiency (Lassiter and Morton 1968), but is also influenced by sheep breed, feed intake (Grace and Sumner 1986) and the method for washing wool samples (Paynter 1982). While Mn in the liver is responsive to changes in intake (Egan 1975; Masters and Paynter 1988) the tissue most affected during deficiency is the heart (Masters *et al.* 1988).

Requirements

Factorial estimates for requirements are not satisfactory. The low coefficient of absorption and low tissue content mean that any small error in the coefficient of absorption will result in a major error in estimates of requirement. For example, Grace (1983*b*) estimated that each kilogram of liveweight gain in a sheep requires approximately 0.5 mg Mn; therefore if the sheep was growing at 100 g/d and the coefficient of absorption was 0.01 (Sansom *et al.* 1978) or, alternatively, 0.14 (Grace 1975; Ivan *et al.* 1983), and the sheep was consuming 1 kg of dry matter, the required concentrations in the diet would be 5 or 0.35 mg Mn/kg DM respectively. The newborn single lamb and other products of conception contain approximately 5.0–7.0 mg Mn. Accumulation by the sheep foetus is highest during the final 50 days of gestation and is 0.05–0.06 mg/d in the singleton foetus near term (Langlands *et al.* 1982; Grace *et al.* 1986). The net requirement per day for foetal growth during the final 50 days of gestation is then similar to the requirements of a sheep growing at 100 g/d. However, the lack of accurate information on absorption of Mn during pregnancy and on total endogenous losses again prevents the conversion of tissue requirements into an estimated dietary requirement.

Skeletal development

Deficiency causes deformed and weak bones with enlarged joints (Hidiroglou 1979); these bones tend to be shorter and have a reduced breaking strength (Rojas *et al.* 1965; Lassiter and Morton 1968). Such bone abnormalities were observed in calves from cows fed as much as 15 or 16 mg Mn/kg DM but were absent when the rations were supplemented to contain 20 mg Mn/kg (Rojas *et al.* 1965; Howes and Dyer 1971). A high proportion of kids (62%) from goats fed 5.5 mg Mn/kg showed some form of paralysis and skeletal damage (Anke *et al.* 1973). These results indicate that 20 mg Mn/kg is necessary for skeletal development. The reports of abnormal skeletal development at intakes of 12–16 mg Mn/kg DM have not been supported by any documented evidence of skeletal defects in grazing ruminants. For example, the amount of Mn in plant material in Australia may, in some locations and at some times during the year, fall below 20 mg/kg DM (Egan 1972; Schultz and French 1978) and some seeds (lupin seed in particular) may contain less than 10 mg Mn/kg (White *et al.* 1981), yet there have been no reports of skeletal abnormalities that are responsive to Mn supplements in ruminants consuming these feeds.

It may be that long periods elapse before body Mn stores are depleted, and that this does not happen in grazing ruminants due to seasonal variation in the Mn content of pasture. If this is so, the previous nutritional history of the animal is as important as the intake of Mn at any one time.

Growth

Severe Mn deficiency (0.8 mg Mn/kg DM) causes a reduction in growth and feed intake in young ruminants (Lassiter and Morton 1968). In cattle, 10–16 mg Mn/kg DM was adequate for growth (Rojas *et al.* 1965; Howes and Dyer 1971), and in rapidly growing young rams fed 13 mg Mn/kg DM, liveweight gain and wool growth were the same as in rams receiving 19, 30 or 45 mg Mn/kg (Masters *et al.* 1988). Panggabean *et al.* (1985) have suggested that sheep consuming a diet high in fibre and low in protein respond to supplements in excess of 35 mg Mn/kg and that the requirements of the rumen microbes for Mn and other trace elements are increased by the consumption of low-quality roughages. This result is supported by Durand and Kawashima (1980) and Arelovich *et al.* (2000) who, from results of *in vitro* studies, both suggest that the optimum dietary content may be as high as 120 mg Mn/kg DM. In support of an effect of Mn on rumen activity, Masters *et al.* (1988) reported that sheep fed 13 mg Mn/kg DM had significantly fewer large rumen bacteria than sheep fed 19, 30 or 45 mg Mn/kg and suggested that this may decrease the amount of bacterial protein leaving the rumen.

Therefore, experiments with animals fed diets deficient only in Mn indicate that 10 mg Mn/kg DM, or possibly even less, is adequate to support growth. However, grazing ruminants are often dependent on diets high in fibre, low in protein or deficient in elements that have a biochemical interaction with Mn, such as Cu and Se. Less is known of the requirements under these conditions although there is some evidence they may be increased.

Reproduction

Deficiency results in impairment of reproductive function in both the male and female (Hidiroglou 1979). In the female, oestrus may be depressed or delayed and more services per conception are required in Mn-deficient sheep, cattle and goats (Rojas *et al.* 1965; Anke *et al.* 1973; Hidiroglou *et al.* 1978). These effects have occurred in animal house studies at intakes ranging from 7–17 mg Mn/kg DM. In the field, reproductive responses have been observed in sheep consuming 14–37 mg Mn/kg (Egan 1972) or in cattle consuming 40 mg Mn/kg (DiConstanzo *et al.* 1986). Both in the field and animal house an increase in the number of services per conception has consistently been associated with low dietary Mn and on some occasions this has resulted in decreased numbers of offspring (Egan 1972). Masters *et al.* (1988) reported slower growth in testicular size (relative to liveweight gain) in young rams fed 13 mg Mn/kg DM compared with rams fed >19 mg Mn/kg DM.

The collective results on reproduction suggest Mn may specifically affect production of, or responses to, reproductive hormones. Others have indicated this may be through synthesis of steroid hormones or secretion of progesterone (Hostetler *et al.* 2003).

Toxicity

The Mn content of pastures is variable, and while some pastures contain less than 20 mg Mn/kg DM others, particularly those on acid soils, can contain up to 1400 mg/kg. High dietary

concentrations may cause a decline in animal performance. In one study, 2600 mg Mn/kg caused a reduction in feed intake and growth rate in calves (Cunningham *et al.* 1966), and in another reduced growth rates were observed in lambs given Mn dosages equivalent to grazing pastures containing 400–700 mg/kg DM (Grace 1973). Paynter (1987*b*) fed sheep diets containing up to 2400 mg Mn/kg for 12 weeks and there were no effects on growth or wool production. It was suggested that while high intakes given as an oral dose once per day (Grace 1973; Cunningham *et al.* 1966) may decrease liveweight gain, high Mn in pastures or mixed with the diet is less likely to have a toxic effect. Although seeds such as lupins may contain more than 2000 mg Mn/kg DM (White *et al.* 1981), pastures rarely contain more than 1000 mg Mn/kg. Adverse affects on production due to high concentrations in pasture are therefore unlikely.

Potassium

The body contains *c.* 2 g K/kg W, there being higher concentrations in younger than in older, fatter animals because muscle contains more K than other tissues. There is about 1.8 g K/kg LWG and 1.4 g K/kg milk. Estimates of requirements made by the ARC (1980) and NRC (1984, 1985*a*) indicate a general value of 5 g K/kg DM, though the NRC (2001) proposes the higher value of 10–12 g/kg DM for lactating dairy cows.

West *et al.* (1987) reported increases in feed intake and milk production by cows during hot weather (daily maxima of >35°C) in response to K supplementation of their high-grain rations to 15.3 g K/kg DM. Cereal grains generally contain less K than forages, but grains grown in Australia appear to contain more K than indicated by some reports on analyses of samples from elsewhere. In any event, the usual intakes of forages, grazed or harvested, virtually eliminate the possibility of K inadequacy. Karn and Clanton (1977) reported a response to supplementary K by steers grazing mature rangeland forages in the USA, which during the winter contained as little as 1 g K/kg DM, but there has been no report or indication of similar circumstances in Australia. Forages generally contain substantially more than the required concentration of K, which is further increased, and Na and Mg reduced, if K fertiliser is applied. Indeed, the prime problem with K in grazing livestock is an excess that reduces the absorption of Mg and promotes hypomagnesaemia (see *Magnesium* for the effects of K on acid-base balance). The maximum tolerable dietary concentration given by the NRC (1980) is 30 g/kg DM, which may be approached or exceeded in pastures, with consequent adverse effects on Mg metabolism. Toxicity and death has been reported in young calves given a liquid diet containing 58 g K/kg DM (Blaxter *et al.* 1960) and in older animals (0.5 yr, 260 kg W) given 0.58 g K/kg W (Neathery *et al.* 1979).

Selenium and vitamin E

Clinical and subclinical deficiencies of Se, leading to widespread losses in production from grazing livestock, have been diagnosed in many regions of the world. Australia has been no exception and both clinical and subclinical deficiencies can occur throughout extensive regions of all States, but at present they have not been reported in the Northern Territory. Regions with low Se tend to be confined to areas of higher rainfall (>500 mm) with high livestock intensity, but isolated areas also occur in regions of medium to lower rainfall. A map showing locations where livestock are at risk from Se deficiency and toxicity is given in a review by Judson and Reuter (1999). Soils originating from volcanic rock are more likely to be Se deficient.

Prior to its recognition as an essential element, Se had been considered as a toxic substance. Its accumulation in plants of several genera growing in seleniferous soil in regions of the central United States is responsible for the disease of grazing livestock known as 'alkali disease' or 'blind staggers'. The presence of Se accumulator plants, largely *Neptunia* spp., in small areas of Central Queensland can likewise result in toxicity in livestock grazing in these areas.

The diagnosis of deficiency initially relied largely on the occurrence of clinical symptoms. Recognition that Se-responsive disorders can occur without obvious clinical symptoms subsequently resulted in much larger areas of land being classified as inadequate or marginally low in Se. This expansion has continued to occur as more surveys are made (Judson *et al.* 1987). Irrespective of such surveys there appears to have been a further increase with time in area, occurrence and frequency of Se-responsive disorders. A similar situation has been observed in New Zealand (Millar 1983).

The factors responsible for these increases have not been clearly defined although the continued application of superphosphate, greater use of S or high-S fertiliser and management factors that increase soil acidity, such as pasture improvement with a high clover component and higher pasture production, which in turn have resulted in higher stocking rates, have all been implicated.

Higher rates of pasture growth in spring leading to a dilution of Se in available pasture, together with increases in the growth rate of livestock and hence in their Se requirements, are considered responsible for the high incidence of Se disorders at this time. Observations that the incidence tends to increase in years of high clover growth would appear to be related to the fact that the Se content of clover is generally lower than that of grass and other pasture species (Davies and Watkinson 1966). Selenium insufficiency also occurs in weaners on dry summer pasture in Western and South Australia but its occurrence is irregular, both within seasons in different locations and between years at the same location. These occurrences are somewhat anomalous because Se concentrations in dry pasture tend to be higher than those in the green phase and factors other than Se *per se* appear responsible (Hunter *et al.* 1982).

Functions

Selenium is capable of exerting multiple actions on endocrine systems by modifying the expression of at least 30 selenoproteins (see review by Beckett and Arthur 2005). Selenoenzymes such as the glutathione peroxidases (GPXs), the thioreductases and the iodothyroxine deiodinases, act as antioxidants and modify redox status and thyroid hormone metabolism. During thyroid hormone synthesis, GPX1 and GPX3 function in the reduction of peroxides and thereby protect cells against oxidative damage. Vitamin E acts at the cell membrane level to prevent the production of free radicals; GSH–Px and vitamin E therefore appear complementary in action.

Several of the selenoenzymes play a vital role in intermediary metabolism (Arthur and Beckett 1994) and in the conversion of thyroxine to tri-iodothyronine in tissue (see Beckett and Arthur 2005). Selenium is also involved in male fertility as GPX4 is essential for the correct development of spermatozoa (Behne *et al.* 1996).

Although Se is an active component of several microbial enzymes, no attention has yet been paid to the possible existence of these enzymes in rumen micro-organisms and, if present, any effects low dietary Se may have on their metabolism. A Se-deficient diet has been shown to alter the composition of the rumen microbial population and rumen metabolism (Hidiroglou *et al.* 1968).

It has recently become apparent that, quite apart from their antioxidant function, Se and vitamin E have an important role in the maintenance of immune function (Arthur *et al.* 2003; Rooke *et al.* 2004). Finch and Turner (1996) have shown that higher concentrations in the diet than those earlier recommended improve animal performance and immune function.

Signs and diagnosis of deficiency

The classical sign of clinical deficiency is white muscle disease or nutritional muscular dystrophy, and now correctly termed Se-responsive nutritional myopathy (NM). It is generally confined to young lambs up to the age of weaning and to young calves up to three to four months of age, though some cases of Se-responsive weaner illthrift occur in southern Australia. Dove *et al.* (1986) found live weight and wool growth responses in Merino lambs following Se-supplementation of the ewes. Lesions associated with Se-responsive NM, which are bilaterally symmetrical, occur predominantly in the most active skeletal muscles, particularly those in the neck/shoulder and thigh regions; lesions can also occur in the heart, and are characteristic of Se-responsive NM, which is uncommon in Australia.

Severe cases of Se-responsive NM can result in death but, in any event, growth rate and wool production are significantly depressed. Reduced growth and wool production are also features of subclinical deficiency as is infertility in adult ewes. Selenium-responsive infertility is caused by embryo loss at or around the time of implantation. Selenium-responsive NM and growth in calves and young grazing cattle are generally infrequent, and usually confined to areas most severely Se deficient. Retained placenta in cows has not been shown to be a Se-responsive condition in Australia, as has been found in some parts of the world. Selenium supplementation has been shown to prevent sub-clinical mastitis in dairy cows in NSW.

Neither physical symptoms of NM nor histopathological examination of affected animals can always be relied upon to confirm clinical deficiency because identical lesions have been found in Se-adequate weaner sheep and were responsive to vitamin E (Steele *et al.* 1980; Hosking *et al.* 1986). Similar myopathies in sheep, such as those associated with lupinosis, have proved unresponsive to treatment with inorganic Se, or vitamin E, or both (Allen *et al.* 1979). Blood or plasma Se concentrations or blood GSH-Px activity are the most commonly used guides to potential problems; liver has sometimes been assayed. Blood GSH-Px is simplest and most economical, but caution is needed in interpreting the results because GSH-Px is synthesised during erythropoiesis and changes in activity, and in Se concentration, are related to the rate of erythrocyte turnover as well as to Se intake. Whole blood GSH-Px activity and Se concentration therefore tend to reflect Se intake over an extended period. Plasma concentrations, on the other hand, are a better indicator of the current intake.

None of these diagnostic indicators can be relied on to predict accurately either the presence of subclinical deficiency or the likely development of a Se-responsive disorder. Considerable overlap in blood or liver Se concentrations between normal, non-responsive animals and those suffering from both clinical and subclinical deficiency has been observed (Gabbedy *et al.* 1977). In addition, blood or liver concentrations can fail to provide an accurate guide to the skeletal muscle concentrations in young sheep at pasture in the Mediterranean environment (Peter *et al.* 1988). At the same time as blood and liver Se are increasing to maxima during summer/autumn, levels in skeletal muscle can decline. Limited data suggest that live weight and wool growth responses are likely to occur in weaner sheep when skeletal muscle concentrations fall below approximately 100 μg Se/kg DM.

Table 3.10 shows marginal bands (based on Underwood and Suttle 1999) for blood, serum, liver and diet Se concentrations in sheep and cattle, which indicate the possibility of benefits in health and production from supplementation.

A partial cost-benefit analysis made by Edwards (1982), using data from WA Department of Agriculture field trials with weaner sheep, indicated that it was economically worthwhile to give Se supplements if there was an increase in wool production of 5% or more only once every three years. The data of Dove *et al.* (1986) also indicate an economic response to Se supplementation. Dose-response trials currently remain the only method of diagnosis of Se-responsive conditions and means of assessing the worth of regular supplementation in areas considered marginally inadequate.

Table 3.10. Marginal bands[A] for indices of Se deprivation in sheep and cattle, with vitamin E not limiting (adapted from Underwood and Suttle 1999)

	Blood (nmol/l)[B]	Serum (nmol/l)	Liver (nmol/kg FW)[C]	Diet (mg/kg DM)[D]
Sheep	500–900	250–500	250–450	0.03–0.05
Cattle	150–250	100–120	200–300	0.02–0.04

[A] Observed mean values that lie within a band indicate a possibility of benefits from Se supplementation, if levels sustained.
[B] Multiply by 0.079 for µg.
[C] Fresh weight.
[D] Multiply by 12.665 for µmol.

Absorption and retention

Absorption occurs largely in the duodenum although metabolism in the rumen appears to be a major determinant of availability. Whereas 0.7–0.8 of dietary Se ingested by non-ruminants is absorbed, net absorption in sheep ranges from 0.3–0.6 (Peterson and Spedding 1963; Wright and Bell 1966; White 1980; Peter *et al.* 1982, 1986). With concentrate diets, the soluble inorganic sources of Se are absorbed before the small intestine whereas the organic sources associated with roughage diets leave the rumen with insoluble particulate matter and the Se is absorbed less efficiently (Koenig *et al.* 1997).

A lower proportion of Se from selenite than from selenomethionine (SeMet) is incorporated into microbial protein (Hidiroglou *et al.* 1968). Metals and heavy metal ions, through complexing with Se, can alter absorption, and microbial metabolism may again influence such reactions.

Absorbed SeMet can be incorporated into body proteins in place of methionine, thereby providing a reversible Se storage from which all Se-containing compounds needed in tissues can be produced. For this reason, and because SeMet cannot be synthesised in ruminants, Schrauzer (2003) has argued that SeMet meets the definition of an essential amino acid. Schrauzer also considers that the requirements for SeMet for different species can be expected to be lower than those provided in the form of inorganic Se salts. However, Koenig *et al.* (1997) found that selenite was as available to sheep as SeMet and that both forms were more available in sheep receiving a concentrate-based diet than in sheep receiving a forage-based diet.

As a consequence of rumen metabolism, faecal excretion is higher than in non-ruminants, and greater than the urinary excretion. The proportions excreted in faeces and urine vary according to the level of intake and form. The relationship between intake of Se and urinary excretion appears to be curvilinear with major increases in urinary excretion occurring after

plasma concentrations reach plateau values. Retention of Se in sheep is dependent on their Se status (Kuchel and Buckley 1969; Lopez *et al.* 1969; White and Somers 1977).

Selenium absorbed from both selenite and SeMet becomes widely distributed throughout the body, concentrations varying between organs and being highest in liver and kidney. Concentrations in skeletal muscle are lower than in cardiac muscle, but because it has a much greater mass than liver, small changes in muscle concentration can account for significant alterations in overall Se retention. Of the 2–3 mg Se contained in a normal adult sheep (50–60 kg W) approximately one-third or more is associated with muscle, while less than one-tenth is contained in the liver despite a concentration that is 2–3 times higher. Blood contains 0.07–0.1 of the body's Se; approximately 0.6 is in the erythrocytes, and of this GSH-Px accounts for 0.9–0.95.

Significant quantities are also associated with hair and wool and are markedly affected by hair colour. About 0.2 of the total Se in young Romney sheep was found in their 200 d growth of fleece (Grace and Watkinson 1985), and a higher percentage may be found with breeds that grow more wool. Plasma and liver concentrations are closely related to dietary concentration while the concentration in muscle is more closely associated with total Se intake (Peter *et al.* 1985).

Transport across the placenta to the foetus appears to be unimpeded and Se concentrations in the blood of the newborn lamb and of the ewe are similar (Hunter *et al.* 1982; Langlands *et al.* 1982).

At term, 0.07–0.09 of the Se in the ewe is in the conceptus, the majority being in the foetus. The content of milk is increased by supplementation (Grant and Wilson 1968; Hunter *et al.* 1982) but Se concentrations are much lower than those in blood or plasma. However, prior to rumen development, net absorption of Se from milk by lambs is similar to that for non-ruminants (0.07–0.08), but in low-Se areas supplementation of ewes fails to prevent a rapid fall in the Se status of the lamb. Availability and absorption presumably decline with the development of a functional rumen.

Requirements

There is currently only one reported attempt to determine the Se requirement of either sheep or cattle at pasture. This attempt, made in New Zealand, involved young sheep growing at a rate of approximately 100 g/d, with a wool growth rate of 10 g/d, which were grazing perennial pasture with 0.03 mg Se/kg DM (Grace and Watkinson 1985). Both the pasture concentration and status of the sheep were considered to be low but adequate. The daily requirement of these sheep was estimated to be 27 μg Se. In deriving this value it was assumed that the absorption coefficient for Se was 0.5, while the value of endogenous loss used was calculated from data reported in the literature. Although the absorption coefficient is within the reported range it is higher than some values obtained with sheep fed roughage diets. Use of a coefficient of 0.4 or 0.3 would therefore have increased the daily Se requirement to 34 or 44 μg respectively, increases of approximately 27–63%. Alternatively, increasing wool production to 15 g/d or endogenous losses by 26%, to 2 μg/d would have increased daily requirements by less than 1 μg and 3μg respectively.

This example clearly demonstrates the critical importance of Se availability and absorption, and the factors affecting these, in determining dietary requirements. A further important determinant of requirement is the physiological state of the animal. This was demonstrated by the study of Se accumulation in the conceptus of ewes at pasture in the low-Se region of

New England in NSW (Langlands *et al.* 1982). It was estimated that ewes at term, with a blood concentration considered to be at the lower limit of adequacy, would need to increase their Se intake by approximately 8 μg/d to maintain their Se status and provide the quantity deposited in the conceptus. It was further estimated that this increase would require a rise in dietary concentration of 0.01 mg Se/kg DM. The change would need to be even greater if the absorption coefficient used in estimation (0.4) had been lower.

In addition to the factors affecting dietary requirement already discussed, the breed of animal, stocking rate, climatic conditions, and the amounts of vitamin E and S in the diet are also regarded as important (Judson *et al.* 1987). Vitamin E has a sparing effect on Se, thereby reducing requirement.

Based on observed occurrences of Se-responsive conditions in New Zealand and Australia, the concentrations considered as adequate for requirements are 0.03 and 0.05 mg/kg DM for sheep and cattle respectively (Judson *et al.* 1987; Millar 1983). The difference undoubtedly reflects differences in the various factors in pasture and animal intakes that influence requirements, and serves to emphasise the difficulty in producing an accurate and simple table of the requirements of grazing animals.

Supplementation

The form of supplement used to correct or prevent deficiency depends to some extent on husbandry practice and the age of the animal. Oral or parenteral treatment with either sodium selenate or sodium selenite has been the traditional method and is still widely used; selenate is the preferred form, being slightly less toxic. Inclusion of Se in drenches or vaccines has become common and where animals are given a regular anthelminthic drench, the procedure is both practical and economic. Likewise, the inclusion of Se in vaccines at lamb marking can serve two purposes at once.

The use of high-density, intraruminal Se pellets (5% elemental selenium, 95% iron) is widespread throughout Australia. Similar pellets, but of larger size and containing 10% elemental Se, are available for cattle. Pellets cannot be safely administered prior to weaning but are effective for lambs when given to suckling ewes (Dove *et al.* 1986). Alternatively, Se may be administered to lambs and calves by drench or injection preferably, as with older animals, at 6–10 week intervals.

Problems of release from pellets associated with the sizes of component mineral particles have been resolved, but the development of encrustations that make the pellets ineffective still appears to be a problem (Langlands *et al.* 1990), despite the administration of steel grub-screw 'grinders'.

Doses administered orally or by injection may be calculated on the basis of 0.1 mg Se/kg W. For simplicity, dose rates per animal are usually 1 and 10 mg respectively for lambs and calves before weaning, and 5–50 mg respectively post weaning. Selenium-responsive infertility in ewes may be treated by use of pellets, or by dosing with 5 mg Se one month prior to mating and again one month prior to lambing to ensure an adequate Se status in the newborn lambs. Selenium drenches for sheep can be effective for up to two months.

Sodium selenate applied to pasture in either superphosphate or 'prills' at a rate of 10 g Se/ha, or at a proportionally higher rate on a small area of a paddock, has been found to be an effective means of improving the Se content of growing pasture and thereby in grazing livestock

(Watkinson 1983; Halpin *et al.* 1985). Australian studies indicate that this method can be effective in elevating blood Se levels of grazing sheep for periods of up to two years (Halpin *et al.* 1985). The method has been registered for use in several States.

Several alternative methods of supplementation exist (Judson 1996). Subcutaneous injection of barium selenate has proven effective in providing long-term protection against Se deficiency, particularly in lambs and calves and is now commercially available in Australia. Oral treatment can be effective in sheep for periods of up to nine months using 'soluble glass boluses' that contain Co and Cu as well as Se, but the Cu they provide could result in undesirably high Cu concentrations in liver and kidney or toxicity, and there may be early regurgitation and loss of the bolus (Judson *et al.* 1988). A commercial bolus (All Trace) containing Co, Cu, I, Mn, Se and Zn is now available in Australia.

In animal (and human) nutrition, inorganic Se salts are increasingly being replaced by feed sources of SeMet such as Se yeast (Schrauzer 2003).

Toxicity

Although Se is a potentially toxic and hazardous element, the recommended rates of supplementation are at least 5–10 times lower than those found to be toxic, and are without risk to animals that do have an adequate Se status. There are, however, a number of reports of accidental poisonings resulting in deaths of livestock on farms; these have arisen through errors in the preparation of oral or injectable supplements (Gabbedy 1970). Acute poisoning results in an elevated temperature and pulse rate, oedema, tissue haemorrhagia, watery diarrhoea and collapse, often followed by death due to myocardial damage and circulatory failure. Sodium selenite is marginally more toxic than sodium selenate with intramuscular injections being more hazardous than the oral or subcutaneous routes.

Sustained ingestion of diets containing from 5–40 mg Se/kg DM results in the classical symptoms of chronic toxicity. Animals suffer a general loss of appetite, appear generally illthrifty with poor coat condition or reduced wool growth, become severally lame, suffer a reduction or loss in vision and, if reproducing, become infertile.

Vitamin E

Vitamin E deficiency, resulting in the occurrence of NM, has been recorded in Victoria and Western Australia in grazing sheep with an apparently adequate Se status (Peet *et al.* 1981; Steele *et al.* 1980; Hosking *et al.* 1986). It may also occur in other States in situations where animals graze dry pasture or crop residues or are fed diets of low vitamin E content for extended periods and, as with subclinical Se deficiency, it is likely that an increasing number of problem areas will be identified. There are currently no confirmed reports of vitamin E deficiency in grazing cattle in Australia although it has been reported in young cattle overseas. Myopathy due to vitamin E deficiency has occurred in young lambs of ewes fed wheat-based diets during pregnancy (Watson and Egan 1985), and during lactation (Watson *et al.* 1988), and in sheep housed for fine-wool production and fed grain/dry roughage diets (Hosking *et al.* 1986).

Vitamin E appears to function at the cell membrane level to prevent the formation of peroxides and subsequent membrane damage through scavenging or removal of potentially damaging free radicals. It thus complements GSH-Px in preventing unregulated oxidation and cell damage. This complementary activity presumably explains why Se and vitamin E appear to have a

mutually sparing effect. Thus, given an adequate level of vitamin E there appears to be a lower requirement for Se, and vice versa.

Despite the complementary action, there are minimum levels for each nutrient at which their sparing effect (or the positive interaction) ceases to apply, and a deficiency develops. Low intakes of both nutrients will therefore predispose animals to develop a responsive deficiency. This interaction may also be a factor in the wide overlapping ranges of Se concentrations in tissues of 'normal' and 'Se-responsive' sheep. Unfortunately, the concentrations of Se and vitamin E in the diet or in animal tissues at which the positive interaction fails to prevent deficiencies occurring are currently poorly defined. Dietary requirements of either nutrient are in future likely to be defined in relation to the dietary content or intake of the other.

The common biologically active form of vitamin E is α-tocopherol. Because a number of other isomers have little or no biological activity, measurements of vitamin E should be made in terms of α-tocopherol rather than total vitamin E. There are currently no well-defined criteria of dietary adequacy for Australian conditions. Furthermore, little is known of dietary availability and the factors affecting this in ruminants, except that from 0.08–0.4 of α-tocopherol administered orally can be destroyed in the pre-intestinal tract (Alderson *et al.* 1971).

Assuming that the ARC (1980) and NRC (1985*a*) recommendations, which are also based on very limited data, were applicable to Australian conditions, the minimum dietary concentration for sheep would lie between 10 and 20 mg/kg DM. Dietary concentrations recommended by the NRC (1985*a*), which are slightly higher than those of the ARC (1980), are 15 mg/kg DM for lambs up to 20 kg W and 20 mg/kg DM for heavier animals including pregnant and lactating ewes. Requirements for cattle (NRC 1984) are even less precise and in the range of 15–60 mg/kg DM. The requirement for α-tocopherol by lactating dairy cattle (NRC 2001) has been increased to about 65 mg/kg DM because of the role of vitamin E in health and immune function. All these values assume an adequate Se intake. The ARC (1980) suggests the concentrations might have to be increased if the dietary Se content is low, but this might not be necessary when nutritional conditions are poor, for example with animals grazing dry pastures and only maintaining, or losing, weight.

In these conditions in Western Australia there was only 0.72 mg α-tocopherol/kg DM in the pasture being grazed by weaner sheep that had a vitamin E-responsive NM (Steele *et al.* 1980). When housed and maintained on a feed containing only 0.39 mg α-tocopherol and 0.02 mg Se/kg DM (Allen *et al.* 1985), these sheep showed spontaneous remission of clinical myopathy, and in those without a subclinical NM the mean α-tocopherol concentration in liver was 4.8 mg/kg wet weight (range 1.3–8.0 mg). The mean α-tocopherol concentration was 1.4 mg/kg wet weight (range 0.4–3.8 mg) in those that after ten weeks still showed a subclinical NM. These results imply that more than 4 mg/kg wet weight indicates adequate vitamin E status though, as with dietary concentration, this is probably dependent on Se status. Allen *et al.* (1985) concluded, however that although α-tocopherol was completely effective and Se partially effective in treating the NM, these two nutrients were not the only factors influencing its occurrence; Gardiner (1962) suggested low pasture Co, secondary anaemias, diarrhoea particularly from parasitic infestations, and various non-specific stresses may be involved in the aetiology. Subclinical NM, which is more widespread than the clinical form, was shown by Fry *et al.* (1996) to have no effect on wool production of weaner sheep in Western Australia during summer and autumn.

The vitamin E status of animals is currently assessed by measurements of α-tocopherol in plasma or liver. Plasma concentrations in lambs of ewes fed a low-Se diet and which developed

NM unless treated with vitamin E or Se, ranged from 2–2.5 mg/l (Whanger *et al.* 1976). Weaner sheep in Western Australia with vitamin E-responsive NM (adequate Se) were found to have mean plasma concentrations below 1 mg/1 and liver concentrations of less than 1 mg/kg wet weight (Steele *et al.* 1980; 1981). Minimum concentrations for adequacy are, like dietary concentrations, dependent on Se status. A plasma value of 3 mg α-tocopherol/l has been suggested as marginally adequate in cattle (NRC 1985*a*) but possible effects of Se status have not been examined.

Vitamin E deficiency is easily prevented by regularly feeding small amounts of green plant material such as lucerne (fresh, hay or chaff). Grain supplements, except for lupins, may be effective, but the α-tocopherol content will decrease during storage. Degree of dehydration, grinding and/or pelleting, and additions of minerals and fat also affect dietary α-tocopherol content. The vitamin can be administered directly by mouth or by intramuscular injection. Doncon and Steele (1988) found that oral treatment of weaner sheep produced a more rapid rise in plasma α-tocopherol than did injection, but the increase was more sustained following injection that also resulted in higher liver α-tocopherol. Optimal dose rates were established, but Doncon and Steele (1988) found 2000 mg α-tocopherol was effective; 1000 mg orally did not significantly increase liver concentration. Although Judson *et al.* (1991) suggested that oral dosage was superior to subcutaneous injection, Smith *et al.* (1996) found that supplementation by subcutaneous injection of an aqueous preparation of α-tocopherol acetate was the most effective means of raising concentrations in both the plasma and liver of sheep. The toxicity of α-tocopherol is very low, and it is unlikely that the maximum tolerable range proposed by the NRC (1987), expressed in relation to feed intake as 1000–2000 mg/kg DM, would be approached or exceeded.

Increased tissue α-tocopherol concentration protects not only membranal lipids but also myoglobulin from oxidation and hence delays the onset of discolouration of fresh meat. This has stimulated interest in the administration of vitamin E to beef cattle with the aim of extending shelf life. Liu *et al.* (1995) have suggested that the administration of about 250 mg/d of α-tocopherol for 126 d before the slaughter of beef cattle could benefit the retail market.

Sodium

The body contains around 1.3 g Na/kg W of which about one-third is in bone and most of the remainder in extracellular fluids. Obligatory losses are low; there is an efficient renal mechanism for conservation and much of the Na that enters the digestive tract from the body, primarily in saliva, can be recovered from the large intestine, though faecal excretion is increased during diarrhoea. Consequently, non-lactating animals that have been given a Na-adequate diet may subsequently maintain health and production during a long period of inadequacy (e.g. Vincent *et al.* 1986). The ARC (1980) estimates that losses through the skin of 500 kg W cattle may be 0.3 and 1.3 g/d in respectively temperate and tropical conditions, and that the fleece of sheep contains 1.1 g Na/kg of which about 0.8 g is in the suint. Milk secretion causes the largest loss; there is around 0.6 and 0.4 g Na/kg of milk from respectively cows and ewes, and much more if they have mastitis.

Signs of Na deficiency include inappetence, loss in body condition and lowered production, none of which is specific to this condition. The first sign is a craving for salt (Underwood 1981) manifested by avid licking of wood, soil, or sweat of other animals, and of salt licks if these are made available. However, all ruminants commonly exhibit an appetite for salt and their use of

licks should not be taken to indicate either a deficiency or a need for Na. The most reliable guide to Na status (Morris 1980) is the Na:K ratio in saliva that is generally greater than 20:1 in Na-replete animals; there is increasing likelihood of a production response to an Na supplement when ratios decrease below about 10:1. Murphy and Connell (1970) have described a simple method of collecting saliva from cattle and sheep for analysis; they recommend the samples analysed should consist of three collections taken from each of a number of animals during a period of a few hours. Sodium levels in spot urine samples, corrected using osmolality or creatinine, are also used to detect Na deficiency in cows.

Occurrence of inadequacies

Forages

There is a quite widespread occurrence of production responses by grazing animals to Na supplementation. Smith *et al.* (1978) examined Na concentrations in 31 species and cultivars of forage plants that they classified as 'natrophiles' or 'natrophobes'. The former, which will generally provide adequate Na for the animal, had Na concentrations in foliage of 3 g/kg DM or more but less in their roots; the natrophobes contained, on average, 1.4 g Na/kg foliage DM and as little as 0.1 g/kg, but larger amounts in their roots.

Forage plants that will generally provide adequate Na (natrophiles) include several grasses (phalaris, ryegrass, cocksfoot, *Bromus* sp.), legumes (white and subterranean clovers, lotus), and crops (barley, oats, marrow-stem and thousand-head kales). Natrophobes, which may have inadequate Na, include *Poa trivialis*, fescue, timothy, kikuyu and paspalum grasses; alsike and red clovers, *Leucaena*, lucerne, lupin, soyabean and *Desmodium* sp.; and some millets, maize, sorghum and rape. Australian reports on animal responses to Na allow the addition of a number of plants to the list of natrophobes (see Minson 1990). There is no doubt that it includes all current cultivars of forage sorghum (Wheeler 1980; Wheeler *et al.* 1983; Mulcahy and Stuart 1987) and some dual-purpose wheats (Dove 2007). It should also be noted here that because the S content of sorghums is generally low relative to the N content (Wheeler and Hedges 1979), and is further reduced because it is used in the detoxification of HCN produced from the cyanogenic material usually present in this forage, access to licks containing S as well as Na can improve the liveweight gain and milk production of animals grazing this feed (Wheeler 1980).

Joyce and Brunswick (1975) reported Na supplements significantly increased liveweight gains, wool growth and milk production by animals grazing lucerne that was growing on pumice soils in New Zealand, and contained only about 0.3 g Na/kg DM. Some responses to Na may be found in southern Australia in animals grazing lucerne or winter wheat. Hall (1982), for example, reported that half of the samples of lucerne obtained from 76 sites in southern NSW contained less than 0.4 g Na/kg DM. Provision of Na supplements (as NaCl) to Merino hoggets grazing winter wheat that contained only 0.06 g Na/kg DM, increased weight gain by 25% (42 g/d) (Dove 2007).

More extensive evidence of low Na status in grazing animals in Australia has come from subtropical and tropical regions. This is consistent with information on several hundred analyses of forages examined by Norton (1982), who found that in 27% of those for tropical grasses and 62% of those for tropical legumes the Na concentrations were less than 0.5 g/kg DM; in contrast only a few of the temperate forages contained less than 1.0 g Na/kg DM. Low Na status has been reported in beef cattle grazing *Panicum maximum* (Gartner and Murphy 1974), and

pastures of *Bothriochloa decipiens* but not of *Heteropogon contortus* (speargrass)/*Stylosanthes* near Townsville, Queensland (Murray *et al.* 1976). However, a supplement of NaCl did increase the liveweight gains of steers grazing *Stylosanthes*/native grasses in the semi-arid tropics near Katherine, Northern Territory (Winter and McLean 1988). Responses to supplementary Na have also been reported by Murphy and Plasto (1973) for beef cows and calves grazing native pastures on the Darling Downs, Queensland; by Kaiser (1975) for calves grazing kikuyu grass (*Pennisetum clandestinum*) at Wollongbar, NSW; by Leche (1977) for cows with calves grazing native pastures in Papua New Guinea; and by Little (1987) for steers fed *Setaria sphacelata* hay. Davison *et al.* (1980) significantly increased the milk yield of cows grazing *Panicum maximum*/*Neonotonia wightii* (glycine) pastures on the Atherton Tableland, northern Queensland, with a supplement of 40 g NaCl/d. A similar supplement might be advisable for dairy cows grazing forage maize or sorghum, or given diets in which the roughage component was silage made from those crops.

If pastures are near the coast, the plants may provide adequate Na even though they could be classed as natrophobes. Smith and Middleton (1978) suggested that the effect of sea spray may extend up to 10 km inland, and found that the Na content of New Zealand pastures decreased as distance from the coast increased. Nevertheless, the response by calves to Na reported by Kaiser (1975) was obtained with kikuyu pastures only a short distance from the coast; the forage contained only 0.3 g Na/kg DM.

There is substantial genetic variation in Na content within forage species, which appears to be a highly heritable character (Bray and Hacker 1981). This is illustrated by the studies of Hacker *et al.* (1985) on 65 accessions from Africa of *Digitaria milanjiana*, which were grown in south-east Queensland. Sodium concentrations ranged from 0.1–23 g/kg DM. In general, the accessions with most Na originated from coastal regions of Africa and those with least Na from inland regions where, in many but not all instances, there was low rainfall. The Na concentrations were negatively correlated with K, as is usual, and Smith and Middleton (1978) suggested that frequent use of K fertilisers (e.g. potassic superphosphate) could promote undesirable reductions in forage Na content (see also p. 146).

Grains

Sorghum grain, like forage, has a low Na content (Morris and Murphy 1972), and this is often so with other grains such as wheat (Saville *et al.* 1973). Consequently, attention should be paid to the Na content of high-grain diets, particularly with lactating cows because of the substantial Na secretion in milk, and especially if the roughage component is fresh or ensiled maize.

When wheat or sorghum grains alone were fed in amounts greater than needed for maintenance, supplementary Na improved the performance of pregnant and lactating ewes (Saville *et al.* 1975), and the growth rates of lambs and calves weaned from ewes and cows that had also been given grain only (Saville *et al.* 1973, 1976). It does not appear to be necessary, however, to provide an Na supplement to survival rations of grain, though loose salt or a salt lick could be a carrier of Ca (see p. 125) and perhaps S (Saville *et al.* 1975) as a rather unreliable method of supplementation (see p. 228). The use of sodium bicarbonate in grain diets to buffer rumen pH is discussed on p. 230 in *Concentrate:Roughage balance*.

Requirements

Factorial calculations and the results of feeding trials yield the following estimates (Morris 1980; Towers and Smith 1983) of sodium requirements (g Na/kg DM):

Pregnant and lactating ewes	0.9
Other sheep	0.7
Lactating cows	1.2
Other cattle	0.8

These estimates for cattle are similar to those of the ARC (1980) that, however, give considerably higher values for sheep because they allow for a daily urinary loss of 20 mg Na/kg W in contrast to their assumption of zero urinary Na loss from cattle. Jones *et al.* (1967) gave timothy hay (0.4 g Na/kg DM) to sheep, which promoted negative Na balances and changes in salivary Na:K ratios indicative of Na insufficiency. Urinary Na excretion was approximately 1.0 mg/kg N per day. It is concluded that other information, which led the ARC (1980) to assume a much higher loss, is insufficiently firm to warrant its use in estimates of the Na requirements of sheep that, in consequence, would then be about twice those given above.

The estimated requirements are minima. High intakes of Na, equivalent to 40–60 g Na/kg DMI supplied as the chloride or bicarbonate in drinking water (Potter *et al.* 1972) or by infusion (Harrison *et al.* 1975), have been shown to increase the fractional outflow rate of liquid from the rumen. These and other studies, reviewed by Harrison and McAllen (1980), indicate consequent increases in the efficiency of microbial crude protein (MCP) synthesis and the proportion of dietary protein escaping ruminal degradation (UDP).

Hemsley (1975) and Hemsley *et al.* (1975) suggested that reduced degradation, giving greater supplies of DPLS (Chapter 2), could account for the increases in wool growth by Merino wethers of 14% (fed every 3 h) to 22% (once-daily feed) that were obtained when the addition of NaCl to their feed and water provided the equivalent of 80 to 100 g Na/kg DMI. The high NaCl intakes caused, as would be expected, some reduction in DMI and a substantial increase in water intake and might, in the long term have had adverse effects on the metabolism of other minerals (e.g. Ca, Mg). They also approached the tolerable limits for NaCl concentrations in feed and drinking water proposed by Wilson (1966*b*), as discussed in *Salinity* (p. 195), which should be consulted for further information.

Sulfur

Sulfur has a number of functions in the body (Moir 1975) but most of it is present in the form of sulfur amino acids (SAA) in the body proteins. The dietary requirements for S, however, are determined primarily by its essentiality for the synthesis of proteins by the ruminal micro-organisms, and for this reason is commonly expressed as a fraction of the N supply from the feed (i.e. S/N, g/g) or as N:S. Harrison and McAllen (1980) found that S/N values reported for mixed rumen bacteria varied from 0.032–0.116 (i.e. N:S = 30.8:1–8.6:1), and the ARC (1980) adopted a mean value of 0.07 (i.e. N:S = 14:1) that is similar to the S/N for body tissues and milk. The S/N for wool, which has a much higher SAA content, is *c.* 0.2 (N:S = *c.* 5:1) (Reis 1979).

The activity of the ruminal micro-organisms, including the fungi (Akin and Hogan 1982), is impaired when there is an insufficiency of S although there is adequate N from RDP. The rates of fermentation in the rumen and passage of digesta from that organ are reduced, resulting in reductions in feed intake, MCP synthesis and OMD. Thus Siebert and Kennedy (1972) and

Kennedy and Siebert (1972) showed that urea plus S, but not urea alone, increased the intake of a speargrass hay (42 g CP/kg DM) by cattle and sheep and increased its digestibility in the sheep. That the digestibility was not increased in cattle may well have reflected a greater recycling of S to the rumen in this species than in sheep (Bray and Till 1975; Kennedy *et al.* 1975; Kandylis 1984). The recycling occurs mainly via saliva, and there is a smaller, variable, net flow between blood and the rumen; the use of SAA for wool growth may account for the difference between the two species.

The use of molasses as a carrier of urea in supplementary feeding (see p. 106) is advantageous because molasses, as well as other attributes, contains substantial amounts of S. The mean concentration in samples from all of the 30 sugar mills in Queensland was 7.3 g S/kg DM with a range of 4.0–14.4 g S/kg DM (Wythes *et al.* 1978).

With other feeds, the S/N requirement should be assessed from their content of RDP rather than of total N, and the following examples of two forages show that the S requirement cannot readily be expressed as a dietary concentration. If one forage contained 80 g CP/kg DM and the other contained 200 g CP/kg DM, with Edg of respectively 0.55 and 0.80 giving 44 and 160 g RDP (approximately 7 and 26 g N), the corresponding available S contents for S/N = 0.07 are *c.* 0.5 and 1.8 g S/kg DM. The S requirement is better related to the DOM intake. With an MCP yield of 130 g/kg DOM (Table 2.5), the N requirement (from RDP) is 20.8 g/kg DOM. The S requirement is therefore about 1.5 g S/kg DOM, which is approximately 0.1 g S per MJ ME. However, as discussed by Durand and Komisarczuk (1988), to allow for unavailability of S and a rate of supply out of phase with the rate of N supply it is probable that there should be 2.5–3.1 g S/kg DOM in order to satisfy microbial requirements.

While S/N = 0.07 appears appropriate for cattle, a rather higher value in the range of 0.075–0.100 has been proposed for sheep (Moir *et al.* 1967–1968), reflecting the lesser recycling. The ARC (1980) notes that many diets would not have an S/N as high as 0.10, and if it were required, a deficiency of S (as distinct from an inadequacy of SAA for maximum wool growth) would be more prevalent than it is in practice. Nevertheless, there are a number of reports from Australia (e.g. Hunter *et al.* 1979; those reviewed by Minson 1982*b*) of responses to supplementary S by animals given forages with less than 1 g S/kg DM. There is widespread occurrence of low soil S in both temperate and tropical regions (Blair and Nicolson 1975; Jones *et al.* 1975) and, as well as the major effect on plant growth, there may be corresponding occurrences of low S in forages.

It is recommended that S/N of 0.08 be **adopted** for sheep, and 0.07 for cattle (i.e. N:S of respectively 12.5:1 and 14.3:1). As a general guide, feeds should contain about 2 g S/kg DM (sheep) or 1.5 g S/kg DM (cattle); 1 g S/kg DM should be regarded as low (Langlands 1987).

It appears that most forms of S in the feed and water, and recycled, pass through the rumen sulfide pool (Bray and Till 1975), and to that extent are available to the micro-organisms. However, reactions of the sulfide with other dietary components affect S nutrition and the metabolism of other minerals. In *Sodium* (p. 161) it was explained that sorghum forage, in addition to a low Na content, can contain cyanogenic substances, and that additional S to allow for the S used in their detoxification to thiocyanate in the rumen can improve animal performance. Excess S, and therefore sulfide, combines with Cu to form its sulfide, and with Mo to form thiomolybdates, which in turn interact with Cu and dietary protein to decrease Cu absorption. Both reactions are involved in the occurrence of induced Cu deficiency (see p. 134). Excess S also interferes with Zn absorption (Lamand *et al.* 1988). The signs and occurrence of acute S toxicity are discussed by Kandylis (1984), and sulfate in drinking water is discussed on p. 197.

High levels of S in water or feed may be a cause of cerebrocortical necrosis (CCN) (see also under *Thiamin (B_1*, p. 184) (Gould 1998). Sulfur intake from all sources should not exceed 0.4% of dietary DM (NRC 1996). Higher levels may lead to over-production of H_2S in the rumen and absorption into the blood stream with associated signs of CCN. Although not leading to CNN, somewhat lower levels of S in the total diet (>0.29%) have been shown to be detrimental to weight gains and carcase characteristics of feedlot cattle (Loneragan *et al.* 2001).

Zinc

Factorial estimation of requirements

The ARC (1980) estimates of Zn requirements for various classes of ruminants are in a number of instances greater than could reasonably be expected to be satisfied by a pasture diet. Subsequent estimates from New Zealand (Towers and Grace 1983*b*) for grazing sheep and cattle are much lower, mainly because higher values are used for the coefficient of absorption. An alternative approach made by Weigand and Kirchgessner (1977*a*) allows for variation in the efficiency of use of absorbed Zn for various metabolic processes, but it is considered that at present there are insufficient data to support a model of this type for ruminants.

Endogenous losses

Observations by Somers and Underwood (1969), Grace (1975), Stevenson and Unsworth (1978*a*, 1978*b*), Masters and Moir (1980) and Suttle *et al.* (1982) suggest that FEL for an immature sheep of 30–40 kg W fed at about the maintenance level is 1–2 mg/d, or about 0.05 mg/kg W, but there is evidence (see SCA 1990) that FEL is directly related to the Zn content of the diet. Estimates for cattle reviewed by the ARC (1980) indicate 0.04 mg/kg W per day.

Observations by Masters and Moir (1980) and Suttle *et al.* (1982) led to an estimate for UEL (sheep) of 0.20 mg/d, or 0.005 mg/kg W. The value of 0.006 mg Zn/kg W per day is chosen for cattle (ARC 1980) that are also assumed to lose 0.003 mg Zn/kg W per day through the skin in sweat and hair.

Total daily endogenous losses **adopted** here are 0.055 mg Zn/kg W for both sheep and cattle. The ARC (1980) value of 0.076 mg/kg W for sheep is higher mainly because it incorporated the only estimate for UEL then available of 0.023 mg/kg W (Grace 1975); for cattle it adopted 0.045 mg Zn/kg W.

Growth

Zinc is not found to any appreciable extent in fat tissue. Consequently the net requirement per kg LWG will probably decrease as the animal increases in size because the proportion of fat in gain increases and of protein decreases (Chapter 1). A wide range of values has been reported for Zn concentration in the carcass, but causes of this variation cannot be clearly identified. In calves Kirchgessner and Neesse (1976) found 38 mg Zn/kg fresh carcass and Williams (1978) found 44 mg/kg. The ARC (1980) adopted 24 mg Zn/kg LWG. There is also a wide range of values for Zn concentration in muscle (fresh weight basis). Those reviewed by Doyle and Spaulding (1978) varied from 22–30 mg/kg for cattle and 24–33 mg/kg for sheep; concentrations in skeletal muscle reported by Lawrie (1981) were respectively 43 and 40 mg/kg. Schricker *et al.* (1982) found higher concentrations in red than white muscle, and average values from mixed muscle sample were 45 mg/kg for cattle and 31 mg/kg for sheep.

From consideration of this information and with allowance for a proportion of fat in gain, and for expression on a live weight rather than carcass or tissue basis, a value of 24 mg Zn/kg LWG is **adopted** for cattle and for fleece-free LWG by sheep.

Tissue catabolism

The effect of liveweight loss on the Zn economy of the animal is uncertain (SCA 1990) but here it will be assumed that the underfed animal will obtain 24 mg Zn/kg liveweight loss that will be used with an efficiency of 1.0.

Wool

A value of 110 mg Zn/kg clean wool is **adopted** (SCA 1990), which is a little less than the 115 mg/kg of ARC (1980) but can be taken to be the minimal requirement for optimal wool production.

Reproduction

More Zn is required for spermatogenesis than for growth but Martin and White (1992) have shown that optimal male fertility can be achieved on a diet with 14 mg Zn/kg DM, much lower than earlier estimates (Underwood and Somers 1969).

The Merino lamb at birth contains about 20 mg Zn/kg fresh weight (Langlands *et al.* 1982; Masters and Moir 1983), but the concentration was reduced to 15 mg/kg when pregnant ewes were given a low-Zn diet that significantly reduced lamb birth weight (Masters and Moir 1983). The majority of Zn deposition occurs during the last trimester and the mean net requirement over this period is assessed as 0.4 mg Zn/kg lamb birth weight (e.g. 1.6 mg/d for a 4 kg single, or 2.8 mg/d for twins together weighing 7 kg). For cattle the ARC (1980) values of 1.1 and 6.3 mg Zn/d in respectively mid and late pregnancy are **adopted**.

Lactation

The Zn content of milk decreases as lactation progresses. Schwarz and Kirchgessner (1975) reported 25 mg Zn/kg of cow colostrum and 4–6 mg Zn/kg milk. White *et al.* (1991) found 12 mg Zn/kg of ewe colostrum and 4.5–6.5 mg/kg milk from ewes grazing pastures containing 30 mg Zn/kg DM. Weigand and Kirchgessner (1982) proposed that 5 mg Zn/kg cow milk is desirable for human nutrition. The ARC (1980) adopted 7.2 mg Zn/kg ewe milk on the basis of unpublished studies, but 5.5 mg Zn/kg is **adopted** here. For cows, 4 mg Zn/kg milk is **adopted**, the same as the ARC (1980) value.

Absorption

Zinc homeostasis is controlled mainly by regulation of Zn excretion in faeces; relatively very little being excreted in urine as is evident from the values for FEL and UEL given above. The potential for true absorption approaches 1.0 from low-Zn diets in the absence of specific inhibiting agents, and apparent absorption increases as the Zn content of the diet decreases to the point where the endogenous loss is the major component of faecal Zn excretion. In lactating cows, apparent absorption was 0.30 with a diet containing 40 mg Zn/kg DM and 0.45 when it contained 17 mg Zn/kg DM (Neathery *et al.* 1973).

In sheep, an apparent absorption of 0.1–0.3 is commonly reported for diets containing 20–30 mg Zn/kg DM. Somers and Underwood (1969), Grace (1975), Stevenson and Unsworth (1978*a*, 1978*b*), Masters and Moir (1980) and Suttle *et al.* (1982), found that apparent absorption approached 0.4 as dietary intakes decreased to less than 10 mg/kg DM and 10 mg Zn/d.

There are few values for the true absorption of Zn in ruminants. Measurements in sheep using ^{65}Zn have been made by Suttle *et al.* (1982) who reported TA of 0.75–0.90 with diets containing 17 mg Zn/kg DM (9 mg/d) and declining to less than 0.04 as Zn intake increased to 225 mg/d.

It is not clear whether the ARC (1980) coefficients of absorption of 0.3 for young growing ruminants and 0.2 for mature animals are true or apparent values. Towers and Grace (1983*b*) adopted TA of 0.3 for grazing sheep and cattle, and 0.5 for milk-fed lambs and calves.

The values for TA **adopted** here are 0.6 for pre-ruminant lambs and calves and 0.4 for older animals (SCA 1990). There is evidence that efficiency of absorption is increased during pregnancy and lactation in pigs and rats (Davies and Williams 1977; Kirchgessner *et al.* 1981) but it is not known if this effect occurs in ruminants. It was not detected by Hansard *et al.* (1968) in pregnant ewes with an intake of 30 mg Zn/kg DM, and no allowance will be made here for variation in TA with pregnancy or lactation. Compared with the ARC (1980) factors, both TA chosen are considered to be more likely values for Zn absorption when used to estimate minimum intakes necessary for optimal animal performance.

Estimated requirements

Factorial estimates for various classes of sheep and cattle are shown in Table 3.11 where the values for DM intakes and animal performance are consistent with the information given in Chapters 1 and 6. The majority of estimates indicate a minimum requirement of 10–20 mg Zn/kg DM, or 1–2 mg Zn/MJ of ME. No allowance has been made for maternal liveweight gain during late pregnancy in the ewe or cow, which is desirable and will increase their Zn requirement. The estimated minimum requirement for cattle at a late stage of growth (400 kg W) is less than 10 mg/kg DM. Newborn lambs and calves have relatively high Zn concentrations in liver, presumably because of the absence of pancreatic and bile secretions while *in utero*, which are thought to be the main secretory pathways for Zn from liver. They will also benefit from colostrum with its high Zn concentration that may persist into early lactation when, it appears from Table 3.11, suckled lambs might ingest less than requirement, but any inadequacy would soon be resolved when they began to graze.

As an example of the requirements of mature animals with a maintenance feed intake, a 35 kg sheep grazing feed with M/D = 8 from a pasture providing 1000 kg DM/ha would maintain itself by eating about 0.85 kg DM/d (6.8 MJ of ME), and grow (say) 4 g/d clean wool. Its estimated minimum dietary Zn requirement is 5.9 mg/d, which is about 7 mg/kg DM or 0.9 mg/MJ of ME. A similar sheep grazing pasture with abundant but low-quality feed (say M/D = 7) could eat about 0.5 kg DM/d. Its consequent liveweight loss of about 0.1 kg/d would provide 2 mg Zn/d, which is approximately its net requirement for endogenous losses (1.93 mg/d), and the additional requirement for wool would be small. However, for maximum wool production in Merino sheep on a high-quality diet, White *et al.* (1994) showed that the dietary requirement for Zn may increase to 25 mg/kg DM.

Table 3.11. Factorial estimates of the critical minimum zinc requirements of various types of sheep and cattle grazing pastures providing 10 MJ of ME per kg DM, of a housed dairy cow (12 MJ/kg feed DM), and a suckled lamb and calf

Animal	Live weight	Feed intake/d		Liveweight gain or milk yield	Clean wool	Net Zn required	Dietary Zn required[A]		
	kg	DM(kg)	ME(MJ)	kg/d	g/d	mg/d	mg/d	mg/kg DM	mg/MJ ME
Grazing									
Growing sheep	20	0.8	8	0.1	5	4.1	10.2	12.8	1.3
	40	1.2	12	0.1	7	5.4	13.5	11.0	1.1
Ewe, late pregnancy[B]	50	1.4	14	0.07 (foetus)	6	5.1	12.8	9.1	0.9
Ewe, lactating	50	2.0	20	1.5 (milk)	6	11.8	29.5	14.8	1.5
Growing cattle	200	5.5	55	0.6	–	25.4	63.5	11.6	1.2
	400	7.0	70	0.6		36.4	91.0	13.0	1.3
Cow, late pregnancy[B]	500	9.0	90	0.4 (foetus)	–	34.0	85.0	9.4	0.9
Cow, lactating	500	12.0	120	10.0 (milk)	–	68.0	170.0	14.2	1.4
Housed cow									
lactating	600	16.0	160	20.0 (milk)	–	113.0	282.0	17.6	1.8
Suckled young (pre-ruminant)									
Lamb	5	0.18[C]	4.4	0.2	3	5.4	9.0	50.0	2.0
Calf	40	0.9[D]	18.0	0.6	–	16.3	27.2	30.2	1.5

[A] Dietary requirement = (net requirement)/TA, where the coefficient of true absorption (TA) is 0.6 for pre-ruminant lambs and calves, otherwise 0.4.
[B] Zero gain in W by maternal body.
[C] 1 kg liquid milk.
[D] 7 kg liquid milk.

Estimates from feeding experiments

Studies with semi-purified diets reviewed by the ARC (1980) indicate 7–10 mg Zn/kg DM is adequate for normal growth and for the alleviation of clinical symptoms of deficiency in lambs and calves, and that 14 mg/kg DM maintains optimal plasma Zn concentration. The latter level is also adequate for optimal male fertility (Martin and White 1992).

Requirements for reproduction by ewes and cows have not been studied in detail. Apgar and Fitzgerald (1985) observed foetal malformation and high lamb mortality when ewes were fed semi-purified diets providing 2 mg Zn/d. Plasma Zn concentrations in the ewes were *c.* 0.25 mg/l, and frothy saliva and parakeratosis indicated Zn deficiency. With similar Zn intake by ewes given another diet, Masters and Moir (1983) observed only a reduced feed intake by the ewes, and smaller lambs, when plasma Zn was 0.3–0.4 mg/l.

Field observations

Reports of naturally occurring Zn deficiency in sheep and cattle are difficult to interpret. Skin lesions, poor growth and/or poor reproductive performance are not specific to Zn deficiency and in many instances deficiency would not be expected because the dietary and plasma Zn concentrations have exceeded 20 mg/kg DM and 0.6 mg/l respectively (ARC 1980; Mills *et al.* 1967). In addition, some animals showing growth and reproductive responses to Zn supplements did not show any increase in plasma concentration (Beeson *et al.* 1977; Price and Humphries 1980; Masters and Fels 1985). In one instance (Mahmoud *et al.* 1983), deficiency was defined on the basis of low concentrations in plasma (0.36 mg/l) and liver (36 mg/kg dry weight, compared with normally more than 100 mg/kg) though dietary concentration (20 mg/kg DM) appeared adequate. The exceptionally low liver concentration indicates that the poor growth, skin lesions, and high mortality with associated anaemia were not the result of a simple Zn deficiency. There is one report of a reproductive response (Masters and Fels 1980); in one year, ewes with 0.56 mg Zn/l plasma grazing pasture with as low as 13 mg Zn/kg DM produced 14% more lambs after supplementation that increased plasma Zn to 0.74 mg/1, but this result was not repeated in following years although plasma and feed Zn concentrations were similar (Masters and Fels 1985).

There are several reports of lack of response to Zn by animals eating feed with similar or lower concentrations than when the above responses were observed (Neathery *et al.* 1973; Bedi and Sawhney 1980; Pond 1983; Suttle *et al.* 1982).

Conclusion

It is difficult to reconcile experimental findings with field observations, and it is evident that the latter are not reliable indicators of requirement. The factorial estimates given here are lower than those of the ARC (1980), which, if realistic, would imply Zn deficiency was not uncommon in practice. This is not so, even in animals producing large amounts of milk or growing rapidly, which have the largest requirements; animals at maintenance have minimal requirements. Estimates when related to ME intake, generally 1–2 mg Zn/MJ, are similar to the estimated requirements of young rats (Weigand and Kirchgessner 1977*b*) and pigs (Hankins *et al.* 1985).

As a general guide, healthy sheep and cattle are unlikely to respond to Zn supplements if their diet contains more than 20 mg Zn/kg DM and if plasma Zn exceeds 0.7 mg/1. Concentrations lower than 20 mg Zn/kg DM are found in dry herbage but are uncommon in green pasture and in supplements containing grain. Zinc in water drunk from galvanised troughs could offset low concentrations in dead, poorly digestible forage, but animals on such feed will have low production and thus a relatively low Zn requirement. Ruminants tolerate high Zn intakes; mild adverse effects may appear at concentrations in feed approaching 420 mg Zn/kg DM, and serious toxicity can occur at about twice this value (ARC 1980).

Other minerals

Possible trace elements

Evidence for the essentiality of arsenic, chromium, nickel, silicon, tin and vanadium has been obtained with animals only in very carefully controlled conditions. Reports by Nielsen (1988, 2000) of a possible prophylactic role for boron in human osteoporosis adds some weight to the

remark of Underwood (1981) that while these elements 'have not been shown to have any practical significance in the nutrition of domestic livestock, experience with selenium suggests that such possibilities should not be dismissed'. However, 'it would probably be difficult to produce a diet (for pigs) that did not contain sufficient of these elements' (Annison 1987), and it would certainly be very difficult with ruminants either hand fed or grazing.

Fluorine

Fluorine is a normal constituent of the body but it has not been shown unequivocally to be an essential nutrient. It is of concern because toxic amounts can occur in feed or water. One source is F present in industrial emissions, such as those from aluminium smelters, which should be minimised by pollution control measures. There can be a high natural abundance of F in the soil or water of a region, and F can be introduced in rock phosphate used for fertiliser or as a feed phosphate supplement.

In the USA it has been suggested (Suttie 1980) that, for diets fed over a long term, F concentrations of 40, 50, or 60 mg/kg DM will not affect the productive ability of respectively heifers, mature cattle or ewes. Some F is transferred from dam to offspring via the placenta and in milk, and Wheeler *et al.* (1985) reported reduced wool growth by the lambs of ewes drinking water containing 30 mg F (as NaF) per kg. In the USA the suggested dietary tolerances are much higher for finishing cattle (100 mg F/kg DM) and feeder lambs (150 mg F/kg DM) than for other classes, presumably because it is assumed they will be slaughtered before chronic fluorosis has had time to develop. Such an assumption can be inappropriate in Australian conditions and there is some evidence that undernutrition enhances the effects of marginally toxic levels of F (Suttie 1980; Wheeler and Fell 1983). It is probably advisable to adopt more conservative values for tolerable F contents such as those of the State Pollution Control Commission (1980), which are, per kg DM, a yearly average of 35 mg, not exceeding 60 mg for more than two consecutive months.

It is generally accepted that dairy cattle are more susceptible to fluorosis than beef cattle or sheep, and they may show signs of this disorder if fed 30–50 mg F/kg DM as soluble fluoride over a period of some years (Shupe 1980; Wheeler and Fell 1983). However, a proportion of the F in practical diets will be in relatively less soluble forms and of lower availability to the animal than, for example, from NaF. Consequently a yearly average of 35 mg F/kg DM will probably not be hazardous. While plants may be contaminated by F from industrial emissions, it appears they absorb and accumulate from the soil little F as such (Stevens *et al.* 2000), as distinct from fluoracetate that is synthesised by some Australian plant species and is a cause of stock poisoning. Even high and prolonged use of superphosphate fertiliser or reactive phosphate rocks, which can increase soil F concentrations significantly, has been found to have little impact on herbage F concentrations (McLaughlin *et al.* 1997, 2001). Fluorine is immobile in soils, accumulating in the top few centimetres of the soil profile (McLaughlin *et al.* 2001), so risks are greatest from fertiliser ingestion in heavily fertilised pastures that are infrequently cultivated (e.g. permanent dairy pastures). However, Grace *et al.* (2005) could find no effect of soil F ingestion on serum or bone concentrations of F in dairy cows.

Account should also be taken of F in water. Harvey (1952*b*) has mapped the concentrations of F in Queensland artesian and sub-artesian waters. The highest concentrations, up to 14 mg F/l, were found to be confined largely to boreholes yielding hot bicarbonate water. Sheep showed signs of fluorosis at concentrations as low as 5 mg F/l, which could also be hazardous for cattle. Evaporation along bore drains or from troughs may increase concentrations to as much as

40 mg F/l. There is little published information on F in waters elsewhere in Australia, though it is available from the Water Resources Commissions. It could be expected that, as in Queensland, surface waters will have low contents, and in cooler climates somewhat more than 5 mg/l might be tolerated because the animals will drink smaller quantities (see Chapter 5).

Analysis of blood or urine will detect fluorosis before the development of the characteristic pitting of incisors ('mottled teeth'), skeletal abnormalities and other non-specific signs such as inappetence. Methods of sampling and analysis are discussed by Wheeler and Fell (1983). Clark and Stewart (1983) state that blood F concentrations are considered to be normal if less than 0.19 mg/1; urinary F concentrations of more than 20 mg/1 are found in chronic fluorosis.

Much higher concentrations are found in acute fluorosis, with a variety of pre- and post-mortem clinical signs. The signs are described in reports from New Zealand of superphosphate poisoning of sheep and cattle (Clark *et al.* 1976; O'Hara and Cordes 1982) where the cause was identified as the F from rock phosphate (see review by Loganathan *et al.* 2003). The poisoning occurred when animals grazed pastures top-dressed during the preceding seven days in moist weather so that the fertiliser adhered to the foliage and not been washed off by rain (more than 8 mm, preferably 25 mm; Stewart *et al.* 1974). Presumably poisoning could occur in similar conditions in Australia, and a suspected case in calves has been reported by Dickson and Mullins (1987). The sources of the rock used in New Zealand to make the superphosphate that caused poisoning were not identified, but the phosphate rocks from North Africa and other continental deposits, including those in Queensland, e.g. Duchess (G. M. Murphy pers. comm.), contain 30–40 g F/kg; this is about twice the F content of the Nauru and Christmas Island phosphates (Underwood 1981). Snook (1962) found that dairy cows could be given 60 g/d of Christmas Island rock as a P supplement without showing signs of fluorosis but, as discussed below, they could accumulate substantial amounts of Cd in their bodies.

Cadmium

Cadmium toxicity in ruminants has not been identified in Australia but Cd concentrations have been reported in the livers and kidneys (but not muscle) of sheep (Langlands *et al.* 1988) and cattle (Koh *et al.* 1998), which exceed the limits for human consumption of 1.25 mg Cd (liver) and 2.5 mg Cd (kidney)/kg fresh weight, set by the National Health and Medical Research Council of Australia (NHMRC). Apart from contamination by industry (Merry and Tiller 1978), the prime source of this Cd in Australia is superphosphate fertiliser, which was made from mainly Christmas Island and Nauru rock phosphates up until the 1990s. These phosphates, like those from Ocean Island, have been formed partially from guano and have been found to contain Cd in the range 40–100 mg/kg rock (Cook and Freney 1988). The Australian fertiliser industry is now increasingly using north African and Florida phosphate rocks, which also contain Cd, but at lower concentrations than those from the island sources (20–60 mg Cd/kg), and concentrations in those from the Georgina Basin in north-west Queensland (e.g. the Duchess deposit) are much lower, 5 mg Cd/kg or less.

Newborn lambs and calves contain only small amounts of Cd. It is accumulated through life from that in pasture and, undoubtedly, from the intake of soil. Langlands (1988) proposed that the higher incidence of Cd contamination of sheep and cattle in Western and South Australia than in other States, which might reflect a greater mean age at slaughter, could stem from soil ingestion during the dry summer period when the animals are grazing sparse senesced herbage from the annual pastures; Langlands *et al.* (1988) found in NSW that sheep accumulated more

Cd when grazed at 20 rather than 10/ha. The regional differences could also reflect variation in plant and soil types (Merry and Tiller 1978). Williams and David (1973) and Tiller (1988) found that there was a greater Cd uptake by several cultivars of subterranean clover and by weeds (e.g. capeweed, *Arctotheca calendula*) than by other leguminous pasture plants or by companion grasses; Cd concentrations in cereal grains and peas are low. These authors also showed that Cd uptake from soil increased with its acidity; plant Cd contents were low at soil pH of around 7, but were increased five- or six-fold at pH 5. Cadmium uptake by plants is also enhanced markedly by increasing soil salinity (McLaughlin *et al.* 1994).

Although there appears to be little risk of fluorosis from the use of Christmas Island phosphate as a P supplement (Snook 1962), it could well cause undesirable Cd concentrations in liver and kidney. The same problem would be likely to occur if an aqueous extract of superphosphate made from the rock was used (Snook 1949) because Williams and David (1973) found that the Cd in it is water-soluble. This could also occur with other forms of supplement manufactured from similar material.

Lead

The ARC (1980) concluded that there is a risk of lead intoxication in ruminants if their feed contains more than 60–100 mg Pb/kg DM and this was confirmed by NRC (2005). Only small amounts of lead are absorbed by plants and the chief reason for high Pb is surface contamination, especially with soil. The Pb absorbed by animals is accumulated mainly in the liver and kidneys, and in bone, but concentrations are low in muscle and milk even after persistently high Pb intakes. The limits for Pb in feed should be set much lower than the NRC (2005) maximum tolerable level of 100 mg Pb/kg DM, in order to avoid exceeding the maximum amount permitted in offal, or any other foods, for human consumption. The limit set by the NHMRC is 39 μmol (8 mg) per kg food DM. Koh and Judson (1986) found that this limit was approached in the livers, and substantially exceeded in the kidneys, of sheep grazing within about 20 km of the Pb-Zn smelter at Port Pirie, South Australia. All of the sheep appeared clinically normal though mean Pb concentrations in their faeces, from eight sets of observations made over a period of about two years, were 16 and 51 mg Pb/kg DM at distances from the smelter of, respectively, 18 and 6 km. Concentrations were presumably lower in their pasture plus soil intakes, and it appears that contamination should preferably be no more than about one-tenth of the maximum tolerable level.

Molybdenum

Molybdenum may be applied to pastures, usually in superphosphate fertiliser, to promote the establishment and growth of legumes. A single application may be necessary for this purpose, but repeated application(s) could induce a Cu deficiency in animals grazing the pasture (see p. 134) and should be made only when a need has been identified from analyses of soil or plant (Robson and Abbott 1987). The Cu:Mo ratio in pasture may be influenced by soil pH and moisture content (Brennan and Bruce 1999). Cattle are less tolerant of Mo than sheep (Underwood and Suttle 1999) and may scour profusely on pastures containing more than 20 mg Mo/kg DM. A diet containing 5 mg Mo/kg DM has been shown to delay puberty in cattle and cause a lower conception rate, effects that did not appear to be associated with the Cu status of the animals (Phillippo *et al.* 1985). NRC (2005) recommends a maximum tolerable level of 5–10 mg Mo/kg feed DM for Cu-adequate cattle and sheep.

Chapter 4

Vitamins

Summary

Ruminants synthesise vitamin C and do not require a dietary supply. Vitamin E is discussed in Chapter 3 under *Selenium and Vitamin E*, and vitamin B_{12} is discussed in Chapter 3 under *Cobalt and Vitamin B_{12}*.

Grazing animals generally do not require supplementary vitamin A, even during drought, because hepatic stores make good a dietary inadequacy. One possible exception is rams, and perhaps bulls, required for breeding after some months on dry pasture. Supplementation may be desirable for lambs and calves weaned early during drought on to grain and dried forage diets, and recommended allowances in feedlot diets for cattle and sheep are tabulated.

Vitamin D requirements are provided by most diets, including fresh and dried forages, and by synthesis in the animal body effected by solar ultraviolet radiation. Supplementation of drought or feedlot rations is unnecessary. Responses to supplementary vitamin D have been reported for lambs in south-eastern Australia grazing forage oats, and there is one report of a response by grazing lambs in Tasmania.

Vitamin K is provided by the diet and rumen microbial synthesis and a deficiency is likely only with the consumption of vitamin K antagonists such as dicoumarol, which is present in a few pasture plants.

Suckled lambs and calves, and those given milk substitutes made mainly from milk products, are unlikely to suffer any deficiency of the B vitamin.

Thiamin may be destroyed in the rumen by the enzyme thiaminase I from the microbial population, or from some plant species. Signs and treatment of the consequent disorder, cerebrocortical necrosis, known also as polioencephalomalacia, are discussed.

Introduction

Farm animals synthesise L-ascorbic acid (vitamin C) from glucose, via glucuronic acid and gulonic acid lactone, and do not require a dietary supply of this vitamin. Vitamin E is closely involved with selenium in metabolism and requirements for this mineral are discussed in Chapter 3 (p. 152) under *Selenium and Vitamin E*. Similarly, cyanocobalamin (vitamin B_{12}) is discussed in Chapter 3 (p. 129) under *Cobalt and Vitamin B_{12}*; the only known function of cobalt in ruminants is its use for the synthesis of B_{12} by rumen micro-organisms.

McDowell (2000) should be consulted for detailed information on the roles of vitamins in metabolism, not discussed here.

Vitamin A

Vitamin A is now known to participate in a wide range of essential functions in animals, in addition to its well-known involvement in vision, especially under low-light conditions. The vitamin itself is a nearly colourless, fat-soluble, long-chain unsaturated alcohol (retinol), based on a β-ionone ring connected to a side chain consisting of isoprene units with alternate double bonds. In retinol, the side chain terminates in an alcohol group but it may also terminate in an aldehyde group (retinal or retinaldehyde) or a carboxyl group (retinoic acid). Vitamin A in animal tissues and milk exists primarily as esters of retinol (retinyl esters), usually retinyl palmitate. The double bond structure of vitamin A means that it can exist in a range of isomeric forms and of the 16 possible isomers, all-*trans* retinol is the parent substance of vitamin A. The retinal involved in the processes of vision is derived from metabolism of retinol, and the retinoic acid involved with tissue differentiation is derived from retinol that is subsequently oxidised via retinal to retinoic acid (Olson 1991). Thus, vitamin A is a generic term used to describe all β-ionone derivatives, other than carotenoids, that exhibit the biological activity of all-*trans* retinol.

The pre-formed vitamin does not occur naturally in the diet of ruminants, but the precursors of vitamin A (carotenoids) are found extensively in plant tissues. Following consumption by animals, carotenoids are converted to retinal and then retinol by specific enzymes in the intestinal mucosa, prior to the storage of retinol in the liver. This process is highly efficient in sheep and goats (McDowell 1989) and also in Holstein cattle, and accounts for their white adipose tissue and milk fat. In cattle in general, and in some breeds of cattle in particular (e.g. Jersey, Guernsey), the conversion is much less efficient; as a result significant quantities of carotene itself can be absorbed, resulting in detectable levels of β-carotene in plasma and yellow pigmentation of body and milk fat. For a given intake of β-carotene/kg LW in such breeds, liver vitamin A storage will be less than in sheep, which accounts for the greater incidence of vitamin A deficiency symptoms in cattle and their higher requirements (see McDowell 2000).

More than 500 carotenoids have been isolated but of these, only about 50–60 exhibit biological activity (Olson 1991) and only four of these (α-carotene, β-carotene, γ-carotene and cryptoxanthine) have major provitamin A activity (see McDowell 2000). In quantitative terms, by far the most important of these for grazing ruminants is β-carotene. The quantity of vitamin A formerly described as 1 IU is equivalent in biological activity to 0.3 μg retinol. The conversion of β-carotene to retinol is influenced by many factors, including animal species, but in ruminants 5–6 μg β-carotene is taken to have the same activity as 1μg retinol (1 retinol equivalent = RE). The β-carotene content decreases as forages mature as it is readily oxidised, so that large losses of vitamin A potency are likely during haymaking and storage. As well as the decrease in the β-carotene content of forages during maturation there is a decrease in the proportion utilised by the animal.

Apart from differences related to the animals species concerned, utilisation of β-carotene and its conversion to vitamin A are influenced by a range of factors, discussed by McDowell (2000) and NRC (2006). Briefly, vitamin A uptake is impaired by conditions that damage the intestinal wall such as parasitism, and in animals that are already vitamin A deficient (Donoghue *et al.* 1983*a*) or are Zn deficient, as Zn deficiency reduces the synthesis of retinol-binding protein (RBP) that transports retinol in plasma. Decreased liver RBP levels can thus result in low serum vitamin A, despite adequate vitamin A in the diet (Chhabra *et al.* 1980). Substantial amounts

(40–80%) of carotene and vitamin A can be degraded in the rumen (Ullrey 1972) and requirements are greater for animals fed diets with high energy density (M/D), such as those containing a high proportion of grain, than for animals given feed of lower M/D. For example, the *in vitro* disappearance of vitamin A during a 24-hour incubation in rumen fluid was 15–20% when donor cattle were fed forage (Rode *et al.* 1990; Weiss *et al.* 1995), but increased to about 75–80% when donor animals were fed high-concentrate diets. This appears related to the effect of lower rumen pH associated with feeding concentrates; low pH causes isomerisation of all-*trans* retinol and de-esterification of retinyl esters to the more labile retinol (DeRitter 1976). This is an issue of concern for cattle fed high-grain, low-carotene diets under feedlot conditions.

For further, more detailed information concerning the β-carotene of feedstuffs, the factors influencing the conversion of β-carotene to vitamin A and the subsequent metabolism of vitamin A, see McDowell (2000) and NRC (2006).

The physiological function of vitamin A that has been best characterised at the biochemical level is its role in vision, in which the aldehyde form of the vitamin (retinal) is utilised in the synthesis of rhodospin (visual purple) in the retina (see McDowell 2000 for discussion). However, the vitamin is involved in a much wider range of functions in the body; the elucidation of the mechanisms of these continues to be an area of active research (e.g. involvement of vitamin A in insulin-like growth factor metabolism (Puvogel *et al.* 2005)). Vitamin A has an involvement in a wide range of physiologically distinct functions, including vision, bone growth, reproduction, the growth and differentiation of epithelial tissues and the immune response (Bendich 1989). Retinol is required for normal vision and for some aspects of reproduction, such as spermatogenesis (Abdulkareem *et al.* 2005). However, many of the actions of vitamin A and especially those related to development and differentiation, involve retinoic acid and 9-*cis*-retinoic acid rather than retinol, and are mediated via specific binding proteins in the cell nucleus. These proteins attach to promoter regions in a range of genes to stimulate transcription and thus affect cell growth, development and differentiation (see Ross 1993 and McDowell 2000 for discussion).

As a consequence of its involvement in a wide range of physiological functions, the symptoms of vitamin A deficiency are complex and progressive and in ruminants (sheep, goats, cattle) are discussed by Frier *et al.* (1974), Ghanem and Farid (1982) and McDowell (1989, 2000). The better-known symptoms include night blindness (historically, the earliest recognised sign), xerophthalmia, papilloedema, convulsive seizures, staggering gait, problems in reproduction, and decreased immune function. In part, published differences in daily requirements for vitamin A can be related to the choice of the response criterion used to judge whether intake is adequate.

Vitamin A requirements

An indication of the range in published requirements of sheep and cattle for vitamin A is shown in Tables 4.1 and 4.2, respectively. All requirements are expressed in metric units, i.e. retinol equivalents (RE = μg retinol)/kg LW. By contrast with SCA (1990), requirements for β-carotene are not given in the present report, due to uncertainties about the quantitative conversion from β-carotene to retinol in the wide range of animal types and feeding situations encompassed in Tables 4.1 and 4.2.

In establishing vitamin A requirements for sheep, NRC (1975) used the prevention of night blindness as a response criterion and used an intake of 17 IU vitamin A (5.1 RE)/kg LW as a starting point for estimating requirements. The needs of finishing lambs and of ewes at

maintenance were obtained by multiplying this value by 1.5, those of replacement lambs, yearlings and replacement ewes by multiplying by 2.5 and those of pregnant or lactating ewes by multiplying by five. NRC (1985*a*) presented evidence that elevated pressure in the cerebrospinal fluid (CSF) was a more sensitive indicator of vitamin A status than was night blindness and that the minimum daily requirement for growing or finishing lambs should be raised to 8–16 RE/kg LW. The higher requirements in Table 4.1 reflect this change. The requirements given in SCA (1990) are also based on the reduction of CSF pressure, and are equivalent to those in ARC (1980), as modified by MAFF (1984*b*).

Table 4.1. Comparative vitamin A requirements for sheep in publications 1975–2006 (all values RE/kg LW)

	NRC (1975)	NRC (1985)	SCA (1990)[A]	NRC (2006)	Present report[C]
Finishing lamb, ewe at maintenance	7.7				
Growing lambs	12.8	14.1	10	[B]	15
Replacement ewes, 60 kg	12.8	14.1	10	30	15
Pregnant ewe, 70 kg	25.5	25.5	20	45.5	30
Lactating ewe, 70 kg	25.5	30	30	53.5	45
Replacement rams, 80–100 kg		16	15	35	20–25

[A] SCA (1990) requirements based on ARC (1980) as modified by MAFF (1984*b*).
[B] Value for growing lambs (100 RE/kg LW) based on single publication (Donoghue *et al.* 1983*b*) in which 100 RE/kg LW was the lowest level fed.
[C] Revised requirements obtained by applying 50% 'safety margin' to requirements in SCA (1990).

Table 4.2. Comparative vitamin A requirements for cattle in publications 1989-2006 (all values RE/kg LW)

	NRC (1989)	NRC (1996)	NRC (2001)[A]	SCA (1990)[B]	Present report[C]
Feedlot beef cattle	–	15	–	20	30
Pregnant beef heifers; cows	–	15	–	30	45
Lactating beef cows; bulls	–	28	–	67 (20)	67 (30)
Growing dairy cattle	13	–	24	–	–
Lactating dairy cows; bulls	23	–	33	–	–
Dairy cows, dry period	23		33	–	–

[A] Based on the increase from 42 to 80 IU/kg LW for calves and growing dairy cattle in NRC (2001) cf. NRC (1989) and assuming 1 IU = 0.3 RE.
[B] SCA (1990) requirements based on ARC (1980) as modified by MAFF (1984*b*), with no differentiation between dairy and beef breeds (see text).
[C] Revised requirements obtained by applying 50% 'safety margin' to requirements in SCA (1990), except for lactating cows (see text).

The NRC (2006) recently revised their estimates of vitamin A requirements for small ruminants, to values markedly higher than in their previous publications (Table 4.1). This reflects, in part, a further change in the response criterion used to define the requirement. NRC (2006) regarded the minimum requirement of 14.1 RE/kg LW in NRC (1985*a*) as equivalent to a basal daily intake, as defined by FAO/WHO (1988), but preferred the use of the FAO/WHO (1988) definition of a safe level of intake, which permits the maintenance of body reserves of vitamin A sufficient to meet requirements during periods of low intake. The minimum requirement

was increased accordingly. As in NRC (1985*a*), the requirement for ewes in lactation was set at 17.6% above their requirement in gestation. The requirement for growing lambs was set at 100 RE/kg LW. This is 7–10 times higher than the estimates in previous reports, but appears based on the results of a single study in which 100 RE/kg LW was the lowest level fed (Donoghue *et al.* 1983*b*).

For both dairy cattle (NRC 1989, 2001) and beef cattle (NRC 1996), estimated vitamin A requirements have increased, though not to the same extent as with sheep (Table 4.2). SCA (1990) did not draw a distinction between these two classes of cattle in its estimated requirements. The increased requirement of 67 RE/kg LW for lactating cows in SCA (1990) reflects the suggested need (ARC 1980; MAFF 1984*b*) to account for the demands of lactation plus pregnancy, since beef cows are usually pregnant for more than half of their lactation period. In MAFF (1984*b*), a similar argument was accepted as valid for dairy cows, though requirements were not increased. However, in SCA (1990), the higher requirement of 67 RE/kg LW is accepted by implication for both beef and dairy breeds.

In the present report, it was felt that estimated vitamin A requirements of both sheep and non-lactating cattle (Tables 4.1, 4.2) should be increased relative to the estimates in SCA (1990), for two reasons:

(*1*) The estimates in SCA (1990) used CSF pressure as the response criterion for judging adequacy and did not make an allowance for the maintenance of body reserves of vitamin A.

(*2*) Research since SCA (1990) has indicated a role for vitamin A in an increasingly wide range of physiological functions (see McDowell 2000; NRC 2006).These include gene regulation by retinoic acid (e.g. Ross and Ternus 1993; Puvogel *et al.* 2005), the steroid hormone-like functions of both retinoic acid and 9-*cis*-retinoic acid (Ross and Ternus 1993) and interactions between reproductive hormones and vitamin A (e.g. McNeill *et al.* 2006). In addition, there is increasing evidence for a biological role for the carotenoids, independent of their role as a source of vitamin A, in both reproduction and the immune response. These aspects are discussed by McDowell (2000) and by Chew and Park (2004).

Although an increase in requirements seemed justified, there is not yet sufficient information on the above roles of vitamin A and the carotenoids to allow quantification of the extent to which estimated requirements should be increased. In the absence of guidance to the contrary, estimates in the present report have been increased by 50% relative to those in SCA (1990), except for lactating cows, where the earlier recommendation was already higher than that in NRC (2001).

Under grazing conditions and provided green herbage is available, ruminant livestock are able to utilize the β-carotene of herbage as their source of vitamin A and can maintain a large reserve of the vitamin as retinol in the liver. These reserves can then be utilised during periods of low dietary supply of carotenoids or vitamin A to maintain circulating levels of the vitamin. This situation usually arises during prolonged drought or a sequence of dry seasons when access to green foliage is limited. Hepatic stores of retinol in older animals can be expected to be adequate to provide for requirements even during long droughts, extending beyond one year duration, as was found with sheep by Gartner and Johnston (1969). Studies in Queensland have shown that cattle have sufficient hepatic stores to provide for their requirements in drought (Gartner *et al.* 1968), even extreme drought (Gartner and Alexander 1966). Southcott and McClymont (1960) detected no clinical signs of vitamin A deficiency in 200 kg Hereford steers, initially 22 months old, which were fed wheat (about 19 MJ of ME/d) with 1% ground limestone for 38 weeks.

Serum vitamin A values fell to as low as 20 μg/l, although concentration in blood is not a reliable indicator of vitamin A status.

Younger animals such as growing lambs have smaller body reserves of vitamin A and thus cannot sustain plasma levels of the vitamin for as long a period as adults. For example, lambs fed a carotene-deficient diet were able to maintain adequate plasma vitamin A levels for 10 weeks, but levels of plasma vitamin A were deficient within 13 weeks (Ghanem and Farid 1982).

The extent of hepatic storage of vitamin A in grazing livestock in Australia is such that there is generally no need to provide a vitamin A supplement to animals grazing dry pasture, even during a prolonged drought. One exception to this generalisation is rams (and perhaps bulls) used for breeding after a period of more than about two months on dry pasture; Gunn *et al.* (1942) showed that in rams consuming low-carotene diets, seminal degeneration was detectable after two months and that after six months they were sterile. A second possible exception is lambs and calves weaned from drought-affected dams, which would be expected to have depleted hepatic stores. Franklin *et al.* (1955) gave wheaten chaff plus wheat, or wheat alone (about 3.7 MJ of ME/d) to seven-month old Merino weaners of about 17 kg W. Mortality of 63% during a 243 day period was reduced to 17% in the group that had been dosed orally with 0.15 g of vitamin A. There appear to be no reports of beneficial vitamin A supplementation of weaners at pasture during drought.

Supplementation of ruminant livestock with vitamin A must be done with care, as an excess of retinol, retinyl acetate or retinyl palmitate can result in toxicity. In mature ewes with daily intakes of either 6000 or 18 000 RE/kg LW over six weeks, Donoghue *et al.* (1979) reported decreases in daily feed intake of about 30 and 50% respectively. These diets also resulted in average weekly plasma retinol concentrations of 187.5 or 150.7 μg/dL respectively, considerably greater than the 100 μg/dL suggested as indicative of toxicity (Eaton 1969). The upper safe dietary limit for sheep and goats has been suggested as 13 500 RE/kg DM (NRC 1987), which would equate to about 400 RE/kg LW in a 50 kg animal consuming 1.5 kg DM per day. The NRC (2006) recommended that in small ruminants, daily intake of vitamin A from retinol or retinyl esters should not exceed 6000 RE/kg LW, and that supplements of retinol or retinyl esters should not be administered or fed for greater than four weeks. It thus appears that hypervitaminosis A is unlikely until the daily oral intake greatly exceeds the requirements in Table 4.1. On the other hand, single doses larger than 30 times daily needs may be administered in some circumstances. It may be advisable to give vitamin A to sheep and cattle offered high-energy diets in feedlots, if they have been brought in after three to four months on dry feed. Speers *et al.* (1981) suggest a single oral dose for cattle of 0.3 g vitamin A will suffice; the dose for sheep would be about one-tenth of this amount. The supplement will generally not be necessary if the animals have been brought in from green pasture because their requirements for retinol not met by feed will probably be provided from hepatic stores.

Vitamin D

Vitamin D, calcium and phosphorus are closely interrelated in normal skeletal development. A deficiency of vitamin D or of P, but with adequate Ca, results in rachitic lesions in growing animals; adequate vitamin D and P with a deficiency of Ca has been found to result in poor skeletal development but not rachitic lesions. There is some evidence (ARC 1980) that administration of vitamin D promotes earlier resumption of oestrus post-partum, and that massive oral doses

(0.50–0.75 g/d) given to dairy cows for a few days before and after calving may give protection against parturient paresis, or milk fever, in susceptible animals. Deficiency during gestation can result in bone abnormalities in the young at birth.

The two main natural sources of vitamin D are ergocalciferol (vitamin D_2, principally plant-derived) and cholecalciferol (vitamin D_3, principally found in animal tissues). Vitamin D_2 and D_3 are generally regarded as having equal biological activity, measured in International Units where 1 IU is equivalent to the antirachitic activity of 0.025 μg of crystalline cholecalciferol (Collins and Norman 1991). Vitamin D metabolism and the factors influencing vitamin D status and activity are discussed by Littledike and Goff (1987), McDowell (2000) and NRC (2006). Briefly, vitamin D precursors stored in the liver are converted to 25-hydroxyvitamin D_3 [25-(OH)D], which is the major form of vitamin D in circulation. Upon passage through the kidney, this is converted to the most biologically active form, 1,25-$(OH)_2$D, which functions like a steroid hormone and contributes to blood Ca and P homeostasis via its facilitation of their transport across the intestinal wall (Wasserman and Taylor 1976) and via enhancement of bone resorption (DeLuca 1984).

Receptor sites for 1,25-$(OH)_2$D have been isolated in a wide range of mammalian tissues (Machlin and Sauberlich 1994) and there is increasing evidence that vitamin D has important functions in addition to its accepted involvement with Ca and P metabolism (see McDowell 2000 for discussion). For example, vitamin D appears to be involved in pancreatic insulin metabolism, metabolism within the skin, haematopoiesis and the functioning of the immune system. These continue to be areas of active investigation (e.g. Cantorna *et al.* 2004; Xie *et al.* 2006).

Under Australian conditions, responses to a vitamin D supplement have been reported for lambs grazing green oats near Sydney and for grazing lambs in Tasmania (Franklin 1953). Caple *et al.* (1988*a*) have confirmed that the vitamin D nutrition of lambs in south-eastern Australia during winter and spring may be inadequate, but there may not be a response to supplementation because of other inadequacies, particularly in Ca nutrition and sometimes in P (see p. 126). Such inadequacies are more likely to occur with green oats than with other forages, and result rather more often in osteoporosis (bone fragility) than in rickets. Apart from possible effects of a high vitamin A content in this feed (Grant and O'Hara 1957), there appears no reason to suppose it contains specific but unidentified rachitogenic factors as was suggested by Franklin (1953).

Despite these examples, as a generalisation there are few instances of vitamin D deficiency in grazing farm livestock, principally because the dominant source of vitamin D for such animals is the conversion of cholecalciferol to vitamin D_3 by solar ultraviolet radiation of the skin (Smith and Wright 1984; Littledike and Goff 1987). Hidiroglou and Karpinski (1989) demonstrated, for example, that the vitamin D status of sheep was improved more effectively by 10 h exposure to sunlight than by a supplement of 2000 IU/day of vitamin D_3. There is evidence that the extent of fleece coverage does influence the conversion in skin of cholecalciferol to vitamin D_3, though even in sheep with heavy wool covering, *in vivo* synthesis made a major contribution to vitamin D status (Andrews and Cunningham 1945).

The difficulty of quantifying this *in vivo* synthesis, the existence of body stores of vitamin D and uncertainties about the Ca and P intakes of animals, make it difficult to be explicit about vitamin D requirements. The requirements presented in SCA (1990) were based on the reassessment by MAFF (1984*b*) of earlier estimates in ARC (1980). For calves and growing cattle, the ARC (1980) estimates were based on studies in which the criterion of adequacy was the

prevention of rickets, though ARC (1980) accepted that higher requirements may be necessary for maximum growth. Accordingly, MAFF (1984*b*) increased the daily requirement for both calves and growing cattle to 6 IU/kg LW. The same requirement was suggested for lambs and growing sheep, though this was based on very limited data (see MAFF 1984*b*). These values for young livestock were accepted by SCA (1990). In NRC (2006), the vitamin D requirement for maintenance or early pregnancy is taken to be 5.6 IU/kg LW, similar to SCA (1990) for growing ruminants. However, for growing lambs, NRC (2006) suggested an additional requirement of 54 IU per 50 g daily liveweight gain. For a 25 kg lamb growing at 250 g/d, this would mean a total requirement of 16.4 IU/kg LW. There are no data under Australian grazing conditions to suggest a similar requirement and accordingly, the earlier requirement of 6 IU/kg LW is retained. However, this value is based on only a few studies (see SCA 1990, MAFF 1984*b*) and may require revision.

MAFF (1984*b*) similarly reviewed the limited data underpinning the ARC (1980) requirements for pregnant or lactating ruminants, plus data published in the intervening years. A requirement of 10 IU/kg LW was suggested and this was accepted by SCA (1990). In early pregnancy, NRC (1990) suggested a requirement of 5.6 IU/kg LW, followed by additional requirements of 213 IU/day in late pregnancy and 760 IU/kg milk in lactation. For a 60 kg ewe, total vitamin D requirements can thus be computed to be 9.2 IU/kg LW in late pregnancy and 18.3 IU/kg LW in lactation, if milk production is 1 kg/day. While the latter value is higher than SCA (1990), the mean for pregnancy/lactation in NRC (2006; 11 IU/kg LW) is similar to the daily requirement for pregnancy/lactation in SCA (1990; 10 IU/kg LW). Accordingly, the latter value is retained, though again it should be stressed that all published requirements are based on limited data.

It should be noted that the *in vivo* synthesis of vitamin D_3 in skin requires that the elevation of the sun be not less than 35°. Solar ultraviolet radiation is attenuated and has very little antirachitic power at lower elevations, which in Australia occur only south of latitude 34°S during the winter months (i.e. Tasmania, Victoria and the areas of South Australia and NSW that lie to the south of the ACT). The antirachitic power of the sun increases with its elevation to the maximum of 90°.

In Australia, periodic lack of benefit from the sun is unlikely to be of importance because body stores of vitamin D in adult animals, even in lactating cows, can make good a dietary deficiency for several months. Calves and lambs usually have sufficient stored vitamin D to supply their requirements for six to fifteen weeks.

Signs of hypervitaminosis D have been reported after intra-muscular injection of 250 mg in cows, 25 mg in sheep, and daily oral administration of 25 mg to calves (ARC 1980). These quantities far exceed the daily requirements discussed above. NRC (1987) suggested that maximum tolerable dietary levels were 25 000 IU/kg diet if such a diet were consumed for less than 60 days, but only 2200 IU/kg diet for diets consumed over longer periods. NRC (2006: p. 154) suggested that normal vitamin D status would be maintained provided daily vitamin D intake did not exceed 100 IU/kg LW and that hypervitaminosis D would be unlikely '…unless overzealous use of dietary supplements or injectable preparations is common practice.' Another possible source of vitamin D toxicity is the consumption of certain plant species (especially *Solanum* spp.) containing a glycoside of 1,25-$(OH)_2$D, which can result in rapid hypercalcaemia and tissue calcification (see Mello 2003; NRC 2006). Species of *Solanum* in which this glycoside has been detected can be found in Australia, but their quantitative significance under Australian grazing conditions has not been established.

Vitamin K

Vitamin K, the last of the fat-soluble vitamins to be discovered, was not discussed by SCA (1990) on the grounds that requirements by ruminant animals were usually met by a combination of dietary supply and rumen microbial synthesis of the vitamin. However, deficiency symptoms have been observed under field conditions and this, coupled with advances in the understanding of the role of vitamin K, warrant its consideration in this revision.

The general term 'vitamin K' describes not a single compound but a series of quinone isomers that exhibit antihaemorrhagic effects in animals. All consist of 2-methyl-1,4-naphthoquinone; the isomers differ in the nature of the side chain (see McDowell 2000 for details). The compound that can be extracted from plant material, phylloquinone, has a phytyl side chain and is referred to as vitamin K_1, whilst the vitamin K-active compounds produced by microbial fermentation are referred to as menaquinones or vitamin K_2. The synthetic form of the vitamin (menadione or vitamin K_3) has no side chain. The metabolism of vitamin K and its involvement in the process of blood clotting is well described by McDowell (2000), who also discusses other possible functions being attributed to the vitamin, such as an involvement in the processes of bone mineralisation.

Green forage is the richest natural source of vitamin K_1. In addition, rumen micro-organisms synthesise large quantities of vitamin K_2, which is subsequently absorbed in the ruminant small intestine (McDowell 2000). Synthesised vitamin K is highly available to the host animal and this, plus the dietary supply, mean that it is not possible to specify a dietary requirement of vitamin K for grazing ruminants. In the preruminant, Nestor and Conrad (1990) concluded that intestinal synthesis of menaquinone-4 was sufficient to meet vitamin K requirements in the period before rumen development.

In grazing ruminants, haemorrhage arising from vitamin K deficiency or clinical responses to vitamin K supplementation are usually associated with the consumption of vitamin K antagonists, principally in one of two forms:

(*1*) Accidental ingestion of the rodenticide warfarin (3-(α-acetonylbenzyl)-4-hydroxycoumarin) that is closely related to dicoumarol (see below) and that greatly perturbs vitamin K-dependent clotting factors.

(*2*) Ingestion of dicoumarol (3,3'-methyl-bis-(4-hydroxycoumarin)), which arises from fungal metabolism of natural coumarins in certain forage plants, if forage conservation techniques are inadequate and mouldy hay is produced. In fresh forage, coumarins do not anatagonise vitamin K because they are bound to glycosides (McDowell 2000). This syndrome has been noted mostly in the USA, associated usually with hay made from the species sweet vernal grass (*Anthoxanthum odoratum*), yellow-flowered sweet clover (*Melilotus officinalis*) and white-flowered sweet clover (*M. alba*) and accordingly has been described as 'sweet clover disease'. The effect of ingested dicoumarol on blood-clotting mechanisms is described in McDowell (2000). Vitamin K therapy by injection will overcome the action of dicoumarol and prevent haemorrhage. Both vitamin K_1 (Alstad *et al.* 1985) and K_3 (Radostits *et al.* 1980) have been successfully used to prevent haemorrhage. Early work with cattle (Goplen and Bell 1967) suggested that vitamin K_1 was more potent than K_3 as an 'antidote' for dicoumarol.

The forage species associated with sweet clover disease do not feature in Australian grazing systems and the pasture species used in Australia do not normally have high levels of coumarins. However, recent interest in gland clover (*Trifolium glanduliferum*; Dear *et al.* 2002; Masters *et*

al. 2006), which contains coumarins, suggests the need for some caution until the quantitative effects of gland clover coumarins are evaluated. In the recent work by Masters *et al.* (2006), coumarin levels in gland clover were of the order of 300 mg/kg DM and coumarin intakes by sheep were less than 600 mg/day. No ill effects on animal health or meat quality were observed, but it should be stressed that this study involved grazing animals. Dicoumarol poisoning in calves has been observed after feeding mouldy sweet clover hay containing >90 mg dicoumarol/kg DM (Alstad *et al.* 1985), which suggests that it would be useful to investigate the effects of forage conservation on coumarin/dicoumarol concentrations in hay made from gland clover, if this species is to be sown more extensively in Australia.

Vitamin B complex

The rumen micro-organisms synthesise all B complex vitamins, which may, therefore, be required as supplements by pre-ruminant lambs and calves offered non-milk substitutes. In weaned sheep and cattle there have been reports of occasional but inconsistent responses to supplements of biotin, choline, folic acid, niacin, pantothenic acid, pyridoxine and riboflavin in housed animals on high-concentrate diets (McDowell 2000, NRC 2006). However, a well-established deficiency of thiamin (vitamin B_1) may be caused by thiaminase associated with feeds or with changed ruminal fermentation.

Pre-ruminant lambs and calves

Newborn lambs and calves have some stores of the B complex vitamin in their tissues (Roy 1980), but are primarily dependent on supplies in milk, or milk-substitute diets until the intake of solid feed promotes development of the rumen. An active microbial population in the rumen will then, usually, synthesise sufficient of all the B vitamins to meet requirements.

The estimates of requirements in Table 4.3, from ARC (1980), also accepted by MAFF (1984*b*), have been derived from experiments with lambs and calves given purified diets, and are the amounts that will be sufficient to prevent the onset of signs of deficiency, not minimum requirements. Concentrations in cow and ewe milks are also shown.

Table 4.3. Vitamin B complex allowances and representative concentrations in cow and ewe milks

	Adequate daily intake	Cow milk		Ewe milk
	(µg/kg W)	Liquid (mg/kg)	Dried (mg/kg)	Liquid (mg/kg)
Thiamin (B_1)	65–150	0.45	3.0	1.2
Riboflavin (B_2)	15–45	1.8	13.5	4.3
Nicotinic acid	260	0.8	6.0	5.4
Vitamin B_6[A]	65	0.4	3.0	0.7
Pantothenic acid	195	3.2	25.0	5.3
Cyanocobalamin (B_{12})	0.4–0.8	0.0035	0.025	0.01
Folic acid	5	0.06	0.45	0.054
Biotin	1.9	0.025	0.20	0.50
Choline	26 000	130	1000	—

[A] Pyridoxine, pyridoxal, pyridoxamine.

Suckled lambs and calves, and those given milk substitutes containing mainly milk products, are unlikely to suffer any B vitamin deficiency (Roy 1980). When pre-ruminants are given milk replacers containing substantial amounts of, for example, fishmeal, soyabean products, or single-cell protein in place of milk protein, it may be desirable to include some B-complex vitamins in the formulation so that their concentrations are at least equal to those found in milk. Roy (1980) makes special mention of B_{12}, but the amounts of thiamine, riboflavin and pyridoxine could also be checked. A study by Al-Ali *et al.* (1985) on the choline requirement of young lambs given milk replacers containing casein as the sole protein, showed that supplementation with choline chloride to provide 9 mg per MJ of gross energy (233 mg/kg DM) was sufficient to prevent the development of fatty livers that is a common symptom of a choline deficiency. The ARC (1980) value for an 'adequate intake' of 26 mg choline/kg W daily may be a substantial overestimate of requirements. It was derived from the results of Johnson *et al.* (1951) who reported the development of an acute choline deficiency syndrome in young calves given a synthetic milk diet; it did not develop in calves given the same diet supplemented with 200 mg choline/kg W. This choline concentration is about twice that in cow milk, and about eight times the concentration that Al-Ali *et al.* (1985) estimated as the requirement of lambs, which was equivalent to about 8 mg choline/kg W.

Thiamin (B_1)

Thiamin occurs in animal tissues mainly as its diphosphate (TPP). It is a necessary co-enzyme for several reactions in carbohydrate metabolism, specifically the oxidative decarboxylation of pyruvic acid to acetyl coenzyme A and in the phosphogluconate pathway. Deficiency will lead to impairment of the TPP-dependent enzyme systems and in nerve conduction, and results in a syndrome described as polioencephalomacia (PEM) or, synonymously and more generally outside the USA, as cerebrocortical necrosis (CCN). Clinical signs of CCN, described in detail by Chapman (1981) and summarised later in this section, are not specific to CCN but diagnosis can be confirmed by thiamin injection and by biochemical tests. The response to an injection by animals with CCN is very rapid, but the treatment should be given as early as possible before cerebrocortical degeneration has become severe.

Biochemical findings in CCN (Edwin and Jackman 1982) include: low concentrations of thiamin in liver, heart and brain (less than 1 μg/g fresh weight compared with normal concentrations of around 2 μg/g or more); accumulation in tissues and blood of intermediates in the tricarboxylic acid cycle such as pyruvate and lactate; lowered activity in tissues of TPP-dependent enzymes, that of transketolase being a direct index of the degree of thiamin deficiency; and significant thiaminase activity in ruminal fluid and faeces. A characteristic sign in post-mortem examination is autofluorescence of the cerebral cortex (Jackman and Edwin 1983; Jackman 1985).

Hill *et al.* (1988) proposed that normal thiamin concentrations in whole blood of sheep and cattle are in the range of 75–185 nmol (25–62 μg) per litre and that concentrations of less than 50 nmol (17 μg)/l are indicative of deficiency.

Thiamin requirements

There is little information on the thiamin requirements of ruminants, but there is substantial information on the requirements of non-ruminants, which are usually expressed in relation to

their energy intake. Because rates of carbohydrate utilisation are similar in these two types of animal (Armstrong 1965), the latter information was used by Edwin *et al.* (1976) to estimate that cattle require about 0.1 mg thiamin per MJ of ME intake. Some support for this estimate is given by Zintzen (1973) who reported that cows require 21–47 mg/d that, with maximum ME intakes during lactation, is equivalent to 0.1–0.2 mg thiamin/MJ. Requirements of sheep could be taken to be similar to those of cattle.

Normally, the requirement will be met by microbial synthesis of thiamin in the rumen. Steinberg and Kaufmann (1977) estimated the synthesis in dairy cows averaged 32 mg/d. Also in dairy cows, the net synthesis measured by Breves *et al.* (1981) was 52 mg/d (s.d. ± 14 mg, $n = 16$) and there was, in addition, a dietary intake of 45 ± 11 mg thiamin/d. In sheep with an ME intake of around 6 MJ/d, Breves *et al.* (1980) reported a daily thiamin flow into the duodenum of between 1.53 and 3.46 mg of which 90–96% (1.44–3.23 mg/d) was of microbial origin; about 90% of the flow disappeared in the small intestines, mainly by absorption. Absorption of thiamin from, and secretion into, the rumen appear to be negligible (Hoeller *et al.* 1977).

Thiamin deficiency – thiaminase

Although thiamin deficiency could be expected in pre-ruminant lambs and calves if dietary intake was low, especially if they initially had low tissue concentrations, the finding that ruminants suffering from CCN were in fact thiamin deficient was at first puzzling. It was shown that the deficiency was not caused by an inadequate rate of thiamin synthesis by the rumen microbes, nor by malabsorption from the gut, but was caused by high concentrations of thiaminase in the rumen that destroyed the vitamin (Edwin and Jackman 1973, 1982).

Thiaminase II (E.C. 3.5.99.2) does not appear to be a significant cause of thiamin destruction in ruminants. The prime culprit is thiaminase I (E.C. 2.5.1.2), a methyl transferase that requires a cosubstrate for its reaction. This enzyme appears to have two effects. In addition to destroying thiamin, there is good evidence that thiamin analogues are formed that are capable of acting as thiamin antimetabolites and thus accentuate the deficiency condition. The types of analogues formed depends on the nature of the cosubstrate that is activating thiaminase I. Roberts and Boyd (1974) extended the range of possible cosubstrates to include commonly used anthelmintics (including piperazene hydrate, oxyclozanide, tetramisole and thiabendazole) and tranquillisers and antihistamines (e.g. trimeprazine, acepromazine), and their findings have obvious implications in the epidemiology of CCN.

Thiaminase I may be present in the diet of ruminants. There are known to be significant amounts in a number of ferns, including bracken (*Pteridium esculentum*), rock fern (*Cheilanthes seiberi*) and Nardoo (*Marsilea drummondii*). The significance of Pteridophytes as hazards to livestock has been reviewed by Chick *et al.* (1985). Italian ryegrass (*Lolium multiflorum*) and tall fescue (*Festuca arundinacea*) have also been reported to contain thiaminase (Ramos *et al.* 2003).

The more common cause of CCN is the development of high thiaminase I activity within the rumen. The enzyme can be produced by a number of species of bacteria, but none has been specifically incriminated (Edwin and Jackman 1982; Wilson *et al.* 1984). It is not understood what changes in the bacterial population result in the high thiaminase I activity, nor what specific conditions in their ruminal environment induce the changes, though Brent (1976) and Gould (1998) have suggested an association with lactic acidosis.

In the absence of thiaminase activity, a high intake of S in feed and water (>0.4% of dietary dry matter (NRC 1996)) and acid conditions in the rumen, which favour the microbial production and subsequent absorption of H_2S, may lead to symptoms of CNN (Gould 1998).

Molasses toxicity may occur in cattle fed on a diet of molasses with urea and very little forage. The clinical signs and encephalopathy are similar to those in CCN, but this toxicity is not thiamin responsive and an association with thiaminase has not been established; deficiencies of a number of vitamins, including thiamin, could be involved in the probable disturbance of carbohydrate metabolism (Edwin and Jackman 1982; Lindsay and Pethick 1983). Molasses toxicity can be reversed by supplying forage, provided this action is taken at an early stage of the disorder.

CCN occurs sporadically in both extensive and intensive systems of animal production in Australia (Gabbedy and Richards 1977), including 'Sharlea' wool production. In this system, Merinos with a fibre diameter of 16.0–17.5 μm are housed and penned in groups of about eight animals. Their fine wool, kept free of dust, vegetable fault, and weathering etc. by plastic coats, is shorn twice a year. Their diet is a least-cost formulation of grain and roughage and, after a period during which an allowance is made for body growth, they are given a maintenance ration.

When high thiaminase I activity occurs there are characteristic signs of CCN: affected animals separate from the group, wander aimlessly, head-press, appear blind and develop ataxia; they eventually fall over and lie with legs extended, kicking intermittently; saliva may drip from the mouth, there is often grinding of the teeth and recumbent animals are usually hyperaesthetic (Chapman 1981). The condition appears to occur more commonly in cold weather. Thiamin deficiency has been confirmed by various diagnostic tests, described in detail by Chapman (1981), and by the response of affected animals to thiamin injections. It has not been found necessary to administer multi-vitamin preparations, which Roberts and Boyd (1974) suggested might be advisable in the treatment of CCN.

Prophylaxis

Animals with thiamin deficiency should be given treatment as early as possible. Affected sheep respond rapidly to an injection of thiamin hydrochloride at the rate of 10 mg/kg W. For routine prophylaxis, 200 g thiamin hydrochloride is dissolved in 1l sterile isotonic saline, the pH adjusted to 3.5 with sodium hydroxide, and stored in a brown glass bottle in a refrigerator. It may be necessary to administer this preparation to Sharlea sheep every two to three months; each animal should be given 250–350 mg thiamin hydrochloride (say 1.5 mL of the preparation) by subcutaneous injection (Chapman 1981).

For cattle with CCN, Kolb (1979) recommends thiamin doses of 200–500 mg for calves and 1–2 g for adults. His recommendation for sheep is 100–500 mg, depending on body weight, and is similar to that of Chapman (1981).

Chapter 5

Water intake

Summary

Measured intakes of water are positively related to feed dry matter (DM) intakes, but the amounts drunk are lower with green, moist pasture or forage than with dry feeds and increase with increasing mean ambient temperature.

Water allowances for various types of cattle and sheep when their feed contains not more than 100 g ash (other than from soil) per kg DM and their drinking water contains not more than 2000 mg total soluble salts (TSS) per litre are given in Table 5.6. The allowances increase with mean ambient temperature.

Requirements increase when the feed is saline (e.g. *Atriplex* spp.) and with increasing TSS in water. A guide to the suitability of saline waters for livestock is given in Table 5.4. Upper limits for the concentrations of major ions and trace elements are given in Table 5.5. Water with growths of blue-green algae is toxic. Considerations in the availability and temperature of drinking water are discussed.

Introduction

Water is the main constituent of the animal's body, amounting to 0.5–0.8 of live weight depending on age and degree of fatness. While an animal may lose almost all of its fat and about half of its protein during starvation yet still survive, the loss of one-tenth of its body water can be fatal.

There are four main functions of water in the body:

(*a*) The elimination of waste products of digestion and metabolism results in a substantial and continuing loss of water. The faeces of healthy cattle often contain 75–85% water, and though sheep faeces are usually drier they are often at least two-thirds water. Cattle urine varies in osmotic pressure from about 100 mOsm during water diuresis to about 1100 mOsm when, during water deprivation, the volume excreted is minimised. Sheep can be still more parsimonious in the latter conditions; urine concentrated to about 3000 mOsm has been reported for adult animals (Macfarlane *et al.* 1961; Brown and Lynch 1972) but only under extreme conditions of dehydration. When water is available, the osmolality of sheep urine is commonly about 800 mOsm even in conditions of high ambient temperature and salt load.

(*b*) The regulation of blood osmotic pressure; the normal value for plasma is about 300 mOsm.

(*c*) Water is a major component of secretions (milk; saliva and other digestive fluids) as well as in the products of conception and in body growth.

(*d*) Thermoregulation, effected by evaporation of water from the respiratory tract and from the skin surface. Evaporative heat loss is minimal at ambient temperatures (T_a) below lower critical (Fig. 1.3), but its importance in maintaining homeothermy increases rapidly as T_a rises. Even within the thermoneutral zone, the loss of heat by evaporation comes to exceed that achieved in total by conduction, convection and radiation, and for each MJ the animal loses as heat by this route it evaporates, and thus loses from its body, approximately 0.42 l of water.

Sources of water

Animals gain water in three ways: by drinking; as water in their feed; and as 'metabolic' water formed during oxidation of nutrients of dietary origin and from the catabolism of body tissue.

The water in the feed can be of major importance. It may comprise as much as 0.9 of the fresh weight of young forage, especially if this has surface moisture gained from rain or dew. Dry mature feed, on the other hand, may contain only 0.1 by weight of water. Thus cattle eating 4.5 kg dry matter daily (M/D = 10), which is approximately the daily requirement for energy maintenance at 350 kg live weight, could gain more than 35 l/d of water in their feed if this was wet pasture but less than 1 l/d if it was dry forage. Although metabolic water is important to the water economy of the animal its contribution is relatively small; the catabolism of 1 kg of fat, carbohydrate or protein yields about 1.1, 0.5 and 0.4 l respectively. With an intake of 4.5 kg DM/d, cattle would gain about 1.5 l water daily from the metabolism of absorbed nutrients, while to gain a similar amount from catabolism of body tissues would require the loss of about 1.5 kg fat or nearly 2 kg protein tissue (i.e. about 0.2 l from the catabolism of the protein in that tissue plus its contained water).

Lynch *et al.* (1972) and Brown and Lynch (1972) found that Merino ewes in the temperate climate of the Northern Tablelands of NSW, deprived of drinking water for 12 months or more, could survive and breed and have similar productivity to ewes with water; non-breeding cattle also may sometimes not drink for long periods. In other climates, deprivation will generally have serious consequences, especially in the arid and semi-arid regions that comprise two-thirds of the Australian continent. Indeed, extensive areas of pastoral lands have been made usable only by establishing watering points, often supplied by bores into underground sources. Many of these sources contain various salts and this problem, which is compounded if there is a high salt intake in the feed (e.g. *Atriplex* spp.), is discussed in *Salinity* on p. 195.

Requirements

An animal's net requirements for water can be calculated as the sum of the minimal losses in faeces and urine, evaporative losses, the water gained by the body in growth and pregnancy, and that lost by secretion in milk. For example, consider a 40 kg lactating ewe (about 1 m^2 surface area) at pasture yielding 1 kg milk/d in an environmental temperature of 15°C, and grazing 1.8 kg/d of dry matter (DM) that exactly met its ME requirements for maintenance (including E_{graze}) plus lactation of about 18 MJ/d (see Chapter 1). The amount of water excreted in faeces would be about 0.8 l/d. Larvor (1983) suggests that the minimal urine excretion required by cattle to eliminate excess electrolytes etc. is 0.9 l/kg DM intake with 'winter' (high-grain) rations and 2.3 l/kg DM when lush pasture with high N and K contents is eaten; sheep urine can be

more concentrated, and a minimum urinary excretion of 2.0 l/d of water by the ewe is assumed. The heat loss of the ewe by conduction, convection and radiation would be about 6 MJ/d so that about 2.5 l/d of water would have to be evaporated to dispose of the remaining 6 MJ of heat produced during metabolism of dietary nutrients.

The total loss of water by the ewe, including the 0.85 l/d secreted in the milk, is thus about 6.2 l/d. In grazing 1.8 kg DM/d the ewe could well gain 7 l/d in the feed plus nearly 1 l/d by metabolism so that, as found by Lynch *et al.* (1972), it would not require drinking water. However, the water requirements for evaporative heat loss could increase three- or four-fold if environmental temperature increased from 15 to 34–40°C, and in the study of Lynch *et al.* (1972) some ewes without drinking water died shortly after they had lambed at a time when mean daily temperature was about 20°C and, owing to lack of rain and dew, the water content of the pasture herbage had decreased to about 0.4. At the same time, similar ewes newly lambed with access to water were drinking about 3 l/d, and in previous months had drunk about 1 l/d, although the performance of the deprived ewes showed this was not necessary for their survival and well-being.

The proportion of the total heat loss by a sheep that is dissipated by evaporation from the respiratory tract, and thus the water loss by this route, will increase with increasing fleece length because of the increasing external insulation (I_e), though at high T_a the heat burden imposed by solar radiation may be substantially reduced by the higher I_e.

Measurements of the water intakes of cattle and sheep do consistently show that the intakes are greater than calculated minimal requirements, and Larvor (1983) suggests that this is because animals 'prefer' to excrete an isotonic (*c.* 300 mOsm) rather than a concentrated urine. Unlike the requirements for any other nutrient, the requirements of animals for water are generally based on observations of how much they voluntarily consume. When a plentiful supply of good-quality water can be provided at low cost it would be foolish to risk loss of animal production by restricting its availability. In the Australian pastoral industries, however, there will be circumstances affecting the frequency and amount of drinking (see *Temperature of Drinking Water*, p. 199).

Relationships with feed dry matter intake

Numerous observations have shown that the total water intake of sheep, goats and cattle is positively correlated with feed DM intake. The ARC (1980) estimates of requirements are based on these observations, and are broadly in agreement with those of INRA (1978) similarly derived. They are for 'livestock in temperate conditions' with environmental temperatures up to 25°C. Calves up to six weeks old are estimated to require 7–8 l water per kg feed DM; the estimates for lambs are 4–6 l water/kg DM at 16–25°C. Estimates for older cattle, not lactating, are in the range of 3.5–7 l water/kg DM, the lower value being for non-pregnant cattle in a cool environment (less than 15°C) and the higher for pregnant animals at higher temperatures (21–25°C); there is an additional allowance of 1 l water per kg milk produced. The corresponding estimates for sheep are up to 40% lower. They vary from 2 l water/kg DM at 15°C or less for growing or adult animals not breeding, to (at 10–25°C) 4.2 or 6.6 l water/kg DM for ewes in late pregnancy bearing, respectively, single or twin lambs, and 6.0 l/kg DM during the first month of lactation; there is no specific allowance for milk production. The estimates for goats given by INRA (1978) vary from 2–4 l water/kg DM and are similar to the estimates for sheep, and are in both instances for temperatures lower than 15°C.

In Australia it is necessary to derive estimates for considerably higher temperatures than those allowed for by ARC (1980). Winchester and Morris (1956) measured the water intakes of

cattle over a range of 4–38°C. At 38°C *B. taurus* breeds drank about 16 l water/kg DM eaten, and *B. indicus* breeds about 10 l water/kg DM.

Water intakes by grazing animals

Measurements have been made of water turnovers by sheep and cattle in a range of pastoral environments in Australia, with varying types of feed and climate, and they are a guide to water needs in practical conditions. The water turnovers have been measured by reference to the rates of disappearance from the animals of doses of tritiated water administered by injection, and represent total water gains by drinking and in the feed (including surface moisture from rain, dew and guttation), and as metabolic water. Turnovers expressed as l/d or as ml/kg W, give an indication of an animal's total requirements though they will to some extent reflect variation in body fatness. Macfarlane and Howard (1966), Macfarlane *et al.* (1966) and Dove and Axelsen (1979) related turnovers in sheep and cattle to kg $W^{0.82}$ to allow for this variation, but provided no evidence that the derived exponent differed significantly from the more usual three-quarter power or from unity. Their approach was based on observations on many species by Adolph (1949) who reported exponents on W, without confidence limits, of 0.88 and 0.82 for relationships with water intakes and urinary water excretions respectively. Richmond *et al.* (1962) found water turnover was related to W with an exponent of 0.80 ± 0.07, but emphasised that this also was an inter-species relationship, and it included no observations on sheep or cattle. In this review, all measurements of water turnovers are expressed as ml/kg W.

Sheep

Observations of water turnovers made by a number of workers are summarised in Table 5.1. The actual amounts drunk will always be less than turnovers. McMeniman and Pepper (1982) measured the amounts of water drunk during a nine-month period by adult Merino wethers browsing mulga (*Acacia aneura*) and found that individual daily intake was related ($r^2 = 0.54$) to both maximum daily environmental temperature (t, °C) and daily rainfall (R, mm/d):

$$\text{Intake (l/d)} = 0.429(\pm 0.307) + 0.073(\pm 0.011)t - 0.013(\pm 0.004)R$$

Thus at 20, 30 and 40°C the predicted intakes are 1.0, 1.8 and 2.5 l/d respectively; these amounts decreasing by 13 ml/d for each 1 mm rainfall. Luke (1987) used data from earlier studies of sheep to derive an alternative relationship:

$$\text{Intake (l/d)} = 0.1911\ t - 2.882\ (R^2 = 0.84)$$

Wilson (1974) found that water intakes by sheep grazing semi-arid pasture were reduced by up to 0.5 l/d when they had access to shade provided by an artificial shelter, but concluded this was not justifiable on economic grounds. Shade had a similar effect on the water intakes of lactating ewes (27 kg W) in north-west Queensland (Stephenson *et al.* 1980), though it did not affect the intakes of low-quality hay that was their sole feed. The ewes kept continuously in shade drank 94 ml/kg W daily during a period when maximum ambient temperature in their environment was 39.9°C; similar ewes directly exposed to the sun (49.3°C maximum T_a) drank 103 ml/kg W. At the same location, Hopkins *et al.* (1978) found that Merino sheep exposed to maximum daily temperatures of about 40°C lost by evaporation 64% of their daily water intake of 5.2 l, four-fifths of the evaporation was cutaneous, non-respiratory, perhaps more from water that diffused through the skin rather than from sweat glands. Adult Merino sheep grazing wheat stubbles near Canberra, ACT, in late summer consumed 65–86 ml/kg W.

Table 5.1. Water turnovers in grazing Merino (M) or Border Leicester (BL) sheep with access to non-saline water in various Australian environments. Measurements made by reference to the disappearance of injected trltiated water. Range in live weight approximately 30–50 kg.

Animals	Location and vegetation	Period	Mean max temp (°C)	Turnover (l/d)	Reference
M dry ewes	Cunnamulla, Qld				Macfarlane *et al.* 1966
	Mitchell grass Dry (0.81 DM)	Nov.	37	4.3	
	Wet (0.16 DM)	Jan.	33	5.3	
M wethers	Deniliquin, NSW				Macfarlane *et al.* 1967
	Atriplex nummularia	March	29	9.4	
	A.vesicaria/forbs/grasses	March	29	5.8	
	Danthonia grassland association	March	29	5.6	
BL wethers	*Atriplex nummularia*	March	29	13.7	
	A.vesicaria/forbs/grasses	March	29	6.9	
M ewes non-pregnant	Armidale, NSW Ryegrass/clover	May	11	4.4	Lynch *et al.* 1972
non-pregnant		Oct.	20	5.2–6.1	Brown and Lynch 1972
non-pregnant		Dec.	25	5.0	
pregnant		Oct.	20	5.6	
lactating		Oct.	20	9.7	
lactating		Nov.	25	6.5	
lactating		Dec.	22	4.6	
M wethers	Deniliquin, NSW *Danthonia*	Oct.–April	22–32	3.1–4.6	Wilson 1974
	Hay, NSW *A. vesicaria*	Oct.–April	22–32	4.9–6.4	
	Ivanhoe, NSW wooded *Stipa* grassland/ *Bassia* shrub	Oct.–April	22–32	4.6–4.9	
M mixed sex	Canberra, ACT Wheat stubble	Feb.–April	–	2.1–2.7	Dove 1984
BL x M ewes lactating	Canberra, ACT Phalaris/sub-clover	July–Sep.	–	5.2–7.2	Dove 1984

There is evidence that water intakes and turnovers vary with genotype. In the studies at Cunnamulla on dry pasture (Dolling and Carpenter 1962; Macfarlane *et al.* 1966) they were greater by 8–14% for Merino sheep selected for high wool production compared with random-bred Merinos, possibly reflecting corresponding differences in feed intakes. At Deniliquin, NSW, daily water turnovers in Border Leicester wethers (Macfarlane *et al.* 1967) were much greater than in Merino wethers when they grazed *Danthonia* grassland (173 *v.* 111 ml/kgW) and when they grazed *Atriplex nummularia* (350 *v.* 196 ml/kg W). The higher water turnovers of the Border Leicesters may largely be accounted for by a higher feed intake, though there is evidence that this breed has a higher water intake per kg feed DM (Wilson and Hindley 1968*a*, 1968*b*).

It can be expected that water requirements will increase during pregnancy and, more particularly, during lactation, but in the field studies that have been made, the effects of reproduction have often been confounded with effects of season.

There is a major effect of vegetation type on requirements. With sheep grazing *Stipa* (grass) and *Bassia* (shrub) in a semi-arid woodland community (Wilson 1974), as much as 7 l/d was drunk and, except for short periods after rainfalls, water was consumed throughout the year. Much higher intakes have been observed with sheep grazing saltbush (*Atriplex* spp.) plant communities. Wilson (1974) reported the maximum amounts drunk varied from 4 l/d when grass was available among the bushes and rainfall was average, to 12 l/d in drought years when no grass was available. There will be corresponding variation in annual water consumption. Estimates made by Wilson (1978), given in Table 5.2, show that the total amount drunk in a year by sheep grazing saltbush may be three to five times the amounts they drink when grass is available.

Table 5.2. Annual water consumption of sheep on natural pastures of western New South Wales (Wilson 1978)

Location	Vegetation	Live weight (kg)	Water consumption (l/yr)
Deniliquin	*Danthonia* grassland	50	400
Hay	*Atriplex vesicaria* with grass, good season	35	600
Hay	*Atriplex vesicaria* without grass, drought	45	2000
Ivanhoe	*Stipa variabilis/Bassia* spp.	60	500

Cattle

There is less information for cattle than for sheep. In the Mediterranean climate of the northern Eyre Peninsula, South Australia, where mean maximum temperatures vary from about 16°C in mid-winter to around 30°C in mid-summer, Wright and Ashton (1978) measured water consumption by breeding Red Poll cows throughout three years. The cows grazed annual pasture of ryegrass/barley grass/medics, and cereal stubbles. Mean daily consumption per cow over the three years was 35 l (approx 90 ml/kgW). It was least during July, 22 l/d, two months after calving and greatest during November–December, 50 to 53 l/d, the time when the calves were weaned.

Springell (1968) measured water turnovers in British breeds (Hereford and Hereford × Shorthorn), Afrikander, and British × Brahman or Afrikander steers grazing native pasture at Rockhampton, Queensland. Mean turnover for all breeds from measurements made at five times during a 13-month period was 30.3 l/d (105 ml/kg W) and was much greater in January (156 ml/kg W) than in the cooler months of April, July or October (85, 91 and 75 ml/kg W respectively). Siebert and Macfarlane (1969) reported a similar range of values for various breeds of cattle in the humid tropics of north Australia and for Shorthorns at Alice Springs in central Australia (Table 5.3). Turnovers were greatest when relative humidity as well as temperature was high and, as observed also by Springell (1968), tended to be higher in *B. taurus* than in *B. indicus* breeds. Studies by Colditz and Kellaway (1972) with cattle in controlled-environment rooms have confirmed other reports (Winchester and Morris 1956; Phillips 1960) that water intakes by *B. taurus* are generally greater than the intakes by Brahmans. Within *B. indicus*, Afrikanders may drink less than Brahmans (Vercoe *et al.* 1972) and have lower turnovers (Springell 1968), but it appears that one reason why both types have greater heat tolerance than British breeds is their greater ability to sweat and lose heat by cutaneous evaporation (Vercoe *et al.* 1972).

Table 5.3. Water turnovers in Shorthorn (S), Santa Gertrudis (SG) and Brahman cross (BX) cattle at various locations (Siebert and Macfarlane 1969)

Location	Conditions and breed	Mean (max °C)	RH %[A]	Live weight (kg)	Turnover per day	
					l	ml/kgW
Alice Springs, NT	Grass/forbs/browse					
	S, winter, drought	23	—	278	1.8	114
	S, summer, drought,	38	—	314	54.9	175
	summer, feed plentiful	34	—	440	5.0	193
Darwin, NT	Sorghum/grass					
	S, dry season (Sept.)	36	55	293	5.9	89
	S, dry season (Dec.)	34	71	143	3.5	166
	SG, dry season (Dec.)	34	71	294	46.1	157
	SG, wet season	29	84	523	65.2	125
	S, wet season	29	84	322	4.2	168
	BX, wet season	29	84	532	5.6	123
Katherine, NT	S, natural pasture, wet season	31	88	356	6.2	214
	S, *Cenchrus*/*Stylosanthes*, wet season	31	88	400	68.7	172

[A] Relative humidity recorded at 1500 h.

Cowan *et al.* (1978) measured the water intakes of Friesian cows on the Atherton Tablelands of tropical north Queensland during December and January when mean maximum temperature was 28.1°C. Cows in early lactation yielding 13.8 kg milk/d drank 78 l/d, and those in late lactation yielding 8.9 kg/d drank 60 l/d. Intakes were positively related to maximum temperature and hours of sunshine and negatively related to rainfall and relative humidity. The maximum amount consumed by a cow in one drink was 67 l. The pasture grazed had a mean DM content of 0.4 and Cowan *et al.* (1978) estimated water drunk was 0.65 to 0.75 of total intake, in contrast with observations made in a cool temperate climate (mean maximum 16°C) by Castle and Watson (1973) who estimated that dairy cows yielding 17 kg milk/d grazing pasture (0.17 DM) gained only 0.18 of a total daily water intake of 76 l by drinking.

In the warmer temperate climate of Hamilton, New Zealand, where summer temperatures seldom exceed 28°C, the water drunk by dairy cows averaged 17 l/d, which was about 0.3 of their water turnover (Wright and Jones 1974). In that study it was found that turnovers in lactating cows averaged 212 ml/kg W per day and were correlated ($r = 0.72$) with milk yields over the range of 0.7–11 kg/d; in non-lactating cows the mean daily turnover was 160 ml/kg W. In the Goulburn Valley, northern Victoria, when mean maximum temperature was 33.7°C, King and Stockdale (1981) found that dairy cows of about 400 kg W yielding an average 13.2 kg milk/d and with free access to water drank, on average, 67 l/d; this was 0.57 of the estimated total intake of 118 l/d.

Goats

There is little information available, but McGregor (1986) observed that during summer when mean maximum T_a was 25°C, Angora wether goats drank 50% more water per kg fleece-free W

than did Merino wether sheep (Table 5.1) possibly because the goats have lower external insulation (McGregor 1985). Intakes by both species were twice as great at 35°C and small during winter. McGregor (1986) concluded that it would be necessary to provide more water to goats than to sheep when grazing dry, unshaded summer pastures. In general, however, guidelines similar to those for cattle and sheep should be followed for supplying water to goats (AFRC 1998). There are also differences between breeds of goats, e.g. Swiss Saanen and black Bedouin goats (Silanikove 1985). During three days without water, Bedouin goats had higher feed intakes, which were above maintenance, than Saanen goats (merely maintenance). Feed intake was reduced to a similar extent in both breeds during dehydration, with a concurrent increase in DMD, which was greater in the Saanen goats.

Young lambs and calves

In temperate climates, the water needs of sucking lambs and calves eating little or no dry feed will generally be met by their milk intakes, which will provide about 8 l (cows) or 6 l (ewes) of water per kg milk DM. Nevertheless, they should always have access to drinking water that they will use increasingly as their intake of solid feed increases, and may require while still on a liquid diet if milk substitutes are used or ambient temperature is high.

In July-born Angus calves near Canberra, Dove and Axelsen (1979) measured water turnovers of 6.1–9.6 l/d (186–156 ml/kg W) over the first six weeks of life. Corresponding values for crossbred calves were higher (7.1–10.8 l/d; 212–149 ml/kg W). Pettyjohn *et al.* (1963) found that calves, initially 14 d old, grew most rapidly during the following 42 d when their milk substitute diet, given *ad libitum* without solid feed, was reconstituted to 15% dry matter. Mean daily intakes were 2.1 kg DM, 2.3 litres drinking water and 13.3 litres total water. At 10% and 5% reconstitution, DM intakes and water drunk decreased while total water intakes increased. At 20% and 25% reconstitution there were small increases in DM intake, but though water drunk increased to 3.8 and 5.3 l/d respectively, the total water intakes fell to 5.1 and 4.6 l/kg DM respectively. A study by Jenny *et al.* (1978) yielded similar results. When calves are reared intensively for veal, substitutes may be reconstituted to high DM% in an attempt to maximise their DM intake, efficiency of conversion and rate of gain, and perhaps meat quality (Roy 1980), but with the likely reduction in total water intake per kg DM there is risk of dehydration in warm environments. This is because water evaporation and consequent loss from the body will have a major role in thermoregulatory heat loss (Fig. 1.3), and inadequate water intake can lead to hyperthermia and death (Van Es *et al.* 1969).

In a temperate environment, sucking lambs had water turnovers of 1.46–2.79 l/d (239–126 ml/kg W) between days nine and 86 of life, with milk contributing from 100% down to 17% of total water turnover during that period. (Dove 1988). There is evidence that sucking lambs in a tropical environment require substantially more water per kg DM intake than is provided in milk, and must be provided with drinking water. The same is probably true for sucking calves. D. Jordan (pers. comm.) measured the water intakes of lambs kept with their mothers in open yards, with access to shade, at Charleville in central Queensland. The ewes were given a pelleted lucerne diet in various amounts and so differed in milk production. The water drunk by the lambs comprised 0.24–0.50 of their total daily water intakes, which varied from 132–214 ml/kg W; those suckled by ewes with low milk production drank the greatest amounts.

Stephenson *et al.* (1980) held ewes and lambs in open pens, without shade, at Julia Creek, Queensland. During a six-day period when the mean maximum T_a was 49.3 ± 0.9°C the total

daily water intake by the lambs was 200 ml/kg W and the majority, 175 ml/kg W, was gained by drinking. During the same period, lambs and ewes kept in shade experienced mean maximum T_a of 39.9 ± 0.6°C; total daily water intake by the lambs was 124 ml/kg W of which 94 ml/kg W was gained by drinking. Stephenson *et al.* (1980) emphasised that lamb growth and survival in extensive grazing areas in the semi-arid tropics, where there is a continuing risk of heat stress, will be affected importantly by the availability of drinking water as well as by milk intake.

Salinity

Water

Artesian and sub-artesian water is an important source of supply for many of Australia's sheep and cattle, but it often contains carbonates or bicarbonates, chlorides and sulfates of Na, Ca and Mg. Bore waters in Queensland and the Northern Territory usually contain less than 5000 mg total soluble salts (TSS) per l (i.e. 0.5% TSS) and so water quality is generally not a limiting factor in the development of the rangelands in these two States for animal production (Newman 1978). Concentrations of 10 000 to 15 000 mg TSS/1 or even more are not uncommon in other States (Peirce 1968a; Flinn 1980).

The principal component of TSS from bores in Queensland is sodium bicarbonate (60%+) and in NSW and South and Western Australia is sodium chloride (75%+) (Peirce 1966). Newman (1978) reported that Na was the dominant cation in 72% of 900 bore water samples from the Northern Territory rangelands; dominant anions were bicarbonate in 20% of samples, chloride in 20%, sulfate in 5%, and mixtures of these in the remainder. Underground waters in western Victoria, and in geologically similar areas of South Australia, often contain 250 mg Mg/l and concentrations exceeding 600 mg/1 have been reported (Flinn 1980).

The consumption of water containing 1.3% NaCl increased ruminal osmotic pressure in sheep and reduced the size of the microbial population and its metabolic activity (Potter *et al.* 1972); there would probably be similar effects in cattle. Wilson and Dudzinski (1973) found that a decrease in feed intake by Merino wethers caused by the inclusion of 1.5% NaCl in their drinking water could be prevented if the amount of water drunk was not restricted to less than about 4 l/d (4 to 6 l water/kg DM). With water containing 2% NaCl, the provision of more than 3 l/d failed to promote higher feed consumption, and maximum feed intakes were only 0.6 to 0.85 of those by sheep given fresh water. This and other studies have shown that non-breeding Merino sheep are able to tolerate water containing about 1.3% NaCl for long periods. There is an increase in renal plasma flow rate and glomerular filtration rate and the reabsorption of Na and chloride is reduced (Potter 1968). Tomas *et al.* (1973) found that the consumption of water containing 1.3% NaCl had no effect on Mg balance, and only minor effects on Ca and P balances, which were unlikely to be detrimental.

Merinos are able to concentrate their urine so that it maintains a concentration of about 500 m-equiv of NaCl per litre, about 800 mOsm or 3% w/v (Wilson 1966*b*; Wilson and Dudzinski 1973). This is about 30 ml water/g salt that can be taken as an indication of the water requirement for salt elimination. This value is similar to the requirement of 26–30 ml water/g salt estimated by Wilson and Hindley (1968*a*) for three strains of Merinos (fine, medium and coarse wool) given salty diets. British breeds of sheep may be able to tolerate as much salt in their feed or water as Merinos but probably require more water, as indicated by the estimate by Wilson and Hindley (1968*a*) of 36 ml/g salt for Border Leicester sheep that have also been observed to drink

more than Merinos when grazing *Atriplex* spp. (Table 5.1). Because cattle urine is generally less concentrated than that of sheep they will require still more water, perhaps 60 ml/g salt, and be less tolerant than sheep of high TSS concentrations; Saul and Flinn (1985) indicate an upper limit of 8–12 g TSS/l and work reviewed by the ARC (1980) indicates a safe maximum of 10 g TSS/l for adult cattle not breeding or lactating.

In assessing the suitability of water for livestock, account must also be taken of the concentrations of electrolytes in addition to NaCl, and of the type of animal using the supply. Peirce (1959; 1960; 1962) found that Merino wethers could tolerate drinking water containing, per l, 1 g $MgCl_2$ in addition to 12 g NaCl; they could also tolerate 5 g Na_2SO_4 in addition to 9 g NaCl, and 3 g $CaCl_2$ in addition to 10 g NaCl. In further experiments (Peirce 1968*a*, 1968*b*), breeding Merino ewes were provided with saline waters for periods of more than one year. When the water was a 'chloride type' containing 13 g TSS/l (9 g NaCl, 1.5 g $CaC1_2$, 1.5 g $MgSO_4$, 1 g Na sulfate and bicarbonate), or was a 'bicarbonate type' containing 5 g TSS/l (2.1 g NaCl, 2.5 g $NaHCO_3$ and the remainder as Na_2SO_4, $MgSO_4$ and $CaCl_2$) he observed a reduction in the percentage of ewes that lambed. Chloride-type water containing 10 g TSS/l did not have this effect but, as with the higher concentration of 13 g TSS/l, there was evidence of reductions in liveweight gains and wool production by the lambs. With the higher concentration there was also an increased incidence in the lambs of diarrhoea and attendant fly-strike, and higher mortality. No adverse effects of the bicarbonate water on lamb performance were observed. Potter and McIntosh (1974) found that the consumption of water containing 13 g NaCl/l by pregnant ewes increased neo-natal lamb mortality, particularly with ewes bearing twins.

Saul and Flinn (1985) gave Hereford heifers (223 ± 3.1 kg W) water containing 10 or 650 mg $MgCl_2$/kg plus 960 mg Na_2SO_4/l and amounts of NaCl that resulted in TSS concentrations of 5, 7, 9 or 11 g/l. Compared with heifers given fresh water, water intakes were higher and feed intakes and liveweight gains decreased with increasing TSS. Performances did not differ significantly between Mg concentrations, and Saul and Flinn (1985) concluded that its adverse effects are similar to those of Na and not greater as had been supposed. Flinn (1980) made a survey of saline waters in western Victoria and found no evidence to support earlier reports that sulfate was more harmful to livestock than other ions. Sulfate concentration appeared to be of little value in assessing the suitability of water for sheep or cattle, and 1 g/l water or even more may be tolerated.

The definitions in Table 5.4 of the suitability for livestock of waters containing various amounts of TSS (expressed as mg/l water = parts per million) were derived from studies in Victoria (AMRC 1981). More detailed tables are provided in ANZECC (1992) and Robson and Curran (2003).

Table 5.4. Guide to the suitability of saline waters with various concentrations (mg/l = ppm) of total soluble salts (TSS) and magnesium (Mg) (taken from ANZECC 1992)

Category	Type of animal	TSS	Mg
1	Suitable for sheep and cattle of all ages.	<5000	<600
2	Generally unsuitable for lambs, calves and weaners. Caution needed with lactating stock. Suitable for dry mature sheep and cattle.	5000–10 000	<600
3	Suitable for dry mature sheep. Caution needed with cattle if unaccustomed.	10 000–15 000	<600
4	Unsuitable for all stock.	>15 000 with	any level
5	Unsuitable for all stock.	any level with	>600

They are in good agreement with results of other studies made in Australia and elsewhere, and with the recommendations of the NRC (1974). Flinn (1980) suggests that a higher Mg concentration, but not more than 400 mg/l, can be tolerated when TSS does not exceed 5000 mg/l; that up to 600 mg Mg/l can be tolerated with TSS up to 15 000 mg/l; and that water with a Mg concentration exceeding 600 mg/l at any TSS content is unsuitable for all livestock. In general, 10 000 mg TSS/l water produces no ill effects in non-breeding adult sheep and is probably the upper safe limit for non-breeding cattle (ARC 1980; Saul and Flinn 1985). Non-breeding sheep grazing grassy rangeland may tolerate water with 15 000 mg TSS/l, but 20 000 mg TSS/l are nearly always detrimental to production and survival (Wilson 1978).

State Departments offer water-quality testing services (e.g. Robson and Curran 2003), which include water-sampling kits for testing farm dams for pH, salinity and chloride level. If salinity is measured as electrical conductivity, in microsiemens (μS) per cm, this may be converted to TSS (mg/l) by multiplying by 0.64.

Feed

Atriplex spp. may contain, per kg DM, more than 0.3 kg ash including as much as 80 g of Na and more than 40 g of K, mainly as chlorides, as well as similar amounts of oxalate (Wilson 1966*a*, 1966*b*). Sheep grazing this feed may have a daily intake of NaCl that exceeds 200 g, and Wilson (1966*b*) suggested that in these circumstances there should not be more than 0.6% NaCl in their drinking water (say 6000 mg TSS/l). The inclusion of straw treated with alkali in the diet of ruminants substantially increases their intakes of electrolytes. Treatment with caustic soda at the rate of 50 kg per tonne of straw results in an intake of 29 g Na per kg DM of this feed consumed. Animals should be provided with good-quality water (probably not more than 6000 mg TSS/l for non-breeding animals, and less if young or lactating) in quantities sufficient to facilitate elimination of the excess electrolytes (see p. 200).

Masters *et al.* (2005) found that increasing the sodium content of a mainly hay diet up to 80 g Na/kg DM (as chloride) decreased feed intake, digestibility, weight gain, wool growth and fibre diameter in Merino wethers but increased the efficiency of wool growth (g/kg OMI) by 50%. This was attributed to the effect of increased water intake on digesta flow rate out of the rumen, thereby reducing dietary protein degradation and increasing the DPLS available for wool growth, as indicated by Hemsley (1975). This result may present significant opportunities for the use of saline land to grow fine wool.

Other chemical contamination

Acceptable limits to the concentrations of major ions: chloride, nitrate, nitrite and sulfate and of trace elements in the water available to various classes of stock are discussed by ANZECC (1992) and are summarised in Table 5.5. Farmers should also be aware of the possibility of contamination of stock water with organic compounds, particularly pesticides; guideline values for the maximum concentration of a range of pesticides are given in ANZECC (1992).

Blue-green algae and bacterial contamination

Gillett and Yiasoumi (2004) discuss the nature, and effects on livestock, of the rapid growths ('blooms') of blue-green algae (cyanobacteria), which can occur in water supplies, especially those formed by impounding run-off and drainage water from cultivated land and pastures.

Table 5.5. Guidelines for maximum allowable concentrations (mg/l) of major ions and trace elements in drinking water (taken from ANZECC 1992)

	Guidelines
Major ions	
Calcium	1000
Nitrate-N	40 (cattle); 60 (sheep)
Nitrite-N	10
Sulfate	1000
Trace elements	
Aluminium	5.0
Arsenic	0.5
Beryllium	0.1
Boron	5.0
Cadmium	0.01
Chromium	1.0
Cobalt	1.0
Copper	5.0 (cattle); 0.5 (sheep)
Fluoride	2.0
Iron	– (no guideline recommended)
Lead	0.1
Magnesium	(see Table 5.4)
Manganese	– (no guideline recommended)
Mercury	0.002
Molybdenum	0.01
Nickel	1.0
Selenium	0.02
Uranium	0.2
Vanadium	0.1
Zinc	20.0

Pollution with chemical fertiliser and excreta provides nutrients, particularly P, for the growths, which are most rapid when sunshine warms the water and promotes high rates of photosynthesis by the organisms. Livestock commonly drink from the shallow waters at the margin of dams, which provide particularly favourable conditions for the development of blooms, and growths in the warm surface of the deeper water are often moved and concentrated at the margin by wind.

The consumption of only small quantities of the contaminated water, for example less than 1 litre by a 30 kg lamb, can be lethal owing to the presence of neurotoxins or hepatotoxins that are produced by at least six species of cyanobacteria. Levels of contamination in excess of 10 000 algal cells/ml of drinking water may cause trouble, depending on the algal species present (ANZECC 1992).

Farm dams should preferably be deep with a relatively small surface area. Prevention of algal blooms through the management of nutrient input is preferable to chemical control. When blooms occur, stock should be denied access. Phosphorus may be removed from solution in farm dams by dosing with alum and gypsum; Gillett and Yiasoumi (2004) suggest mixing 50 kg ferric

alum per megalitre of water and then adding 50 kg gypsum per megalitre. If the water has not cleared within 2 days, the treatment is repeated at 25–50% of the above rates. Alternatively, an approved algicide may be used. Chemical treatments must not be applied to waterways. Copper sulfate is no longer recommended as a treatment; its effect is short-lived.

Under Canadian conditions, Lardner *et al.* (2005) found that the aeration of water in farm dams and pumping into troughs very largely eliminated bacterial contamination and increased the weight gains of yearling steers by 10%. Similar work has not been reported in Australia.

Temperature of drinking water

With both sheep and cattle, snow can wholly replace drinking water (Butcher 1973; Young and Degen 1980) and theoretically the animal could lose 0.33 MJ of energy as heat to melt 1 kg snow intake. Two matters are of more practical concern in Australia; one is the energy required to raise the temperature of cold water drunk and in the feed to body temperature, especially if the animals are drought-fed in a cold environment, and the other is the possible benefit of cold drinking water to animals in a hot environment.

If a 40 kg sheep in drought in a mean environmental temperature of 5°C were fed 750 g DM/d of a moderate quality roughage (M/D = 8) for its maintenance and drank 2.2 l/d of water (i.e. 3 l/kg DM) with a temperature the same as the environment, then 0.31 MJ would be required to raise the temperature of this water to that of the body, i.e. $[(39–5) \times (2.2 \times 0.00418)]$. Metabolic heat may be used with only 0.5–0.6 efficiency for this purpose (Nicol and Young 1981) in which instance there would be an increase of about 10% in daily maintenance heat production. The effect on the animal could be much more important if the feed was cold and wet, say only 0.12 DM, in which instance the lower critical temperature for both sheep and cattle (Chapter 1) could be increased by 15–20°C during the period of eating (Nicol and Young 1981).

In a hot environment, the main thermoregulatory benefit from drinking water will be gained from its subsequent evaporation from the lungs and skin, which, per l water lost, results in a heat loss of about 2.4 MJ. The intake of cold water as such is much less effective in dissipating excess heat from the body; there will be a loss of about 0.4 MJ per l water intake for each 10°C that it is lower than body temperature. Several studies have confirmed the reports of Ittner *et al.* (1951) and Cunningham *et al.* (1964) that, in hot environments, the amounts of water drunk by *B. taurus* breeds of cattle increase with an increase in its temperature to at least 41°C, the maximum examined.

High intakes of hot water occurred in heat-stressed, fed and food-deprived pregnant goats to the point of being 'excessive' and inducing primary polydipsia (Olsson *et al.* 1995: 309). These workers concluded that heat stress stimulated 'signals from warmth receptors [that] overrode inhibiting influences from receptors signalling hyponatremia and hypoosmality at the 'thirst center' in the hypothalamus'.

It has been found that the lower intakes of water with lower temperatures, in a range below about 20°C, are associated with higher feed intakes, rates of liveweight gain, efficiencies of feed conversion (FCE = kg feed/kg LWG), and milk yields (Lofgreen *et al.* 1975; Rice 1980; Lanham *et al.* 1986; Milam *et al.* 1986). In one study with Brahman × *B. taurus* crossbred cattle (Lofgreen *et al.* 1975), feed intake was lower, not higher, with 18°C than with 32°C water but their FCE was unaltered and similar to that of the *B. taurus* breeds given 18°C water.

Though it may be beneficial to cool drinking water when ambient temperatures are high, this is unlikely to be practicable in Australian rangelands. Artesian bore water may be at boiling point

on emergence, and still have quite a high temperature at watering points a considerable distance along the bore drain. Water from other sources supplied to drinking troughs can become hot if it passes through black plastic pipes laid on the ground surface and in some circumstances it might be advantageous to bury the pipes to minimise this effect.

Availability of water

The availability of water may be limited because of restricted times of access, when adequate trough length and rate of entry of water must be ensured, or because of wide spacing between watering points.

Intermittent availability

In drier areas, ruminants are subject to cycles of dehydration and rehydration. The rumen contains a large reservoir of water that contributes 0.5–0.7 of the water loss between bouts of drinking. Silanikove (1994) points out that, when an animal drinks after a period of dehydration, its rumen volume may exceed its extracellular fluid volume and there can be a large osmotic gradient (20–300 mosmol/kg) between the rumen and body fluids and animals 'are confronted at this stage by two opposing tasks, each of vital importance: (*i*) the need to prevent the osmotic hazard leading to water intoxication; and (*ii*) the need to retain the ingested water, so that it is not missing for the next dehydration cycle'. He challenges the widely held 'osmotic protective mechanism' ascribed to the rumen wall, which prevents haemolysis when ruminants imbibe large amounts of water, and suggests an alternative protective mechanism based on homeostatic responses involving absorbed water recycling via enhanced secretion of hypotonic saliva, along with retention of sodium and carbonic acid by the kidney and a marked reduction in urine formation.

Optimum drinking frequency will vary with the type of animal production. Long intervals between drinks that still allow animals to survive are likely to impair the performance of growing and lactating animals. There is evidence (ARC 1980) that milk production by dairy cows can be adversely affected if drinking water is not continuously available. Burgos *et al.* (2001), for example, found that when water intake was restricted to 0.5 of that consumed by unrestricted animals, cows reduced their meal size and feed intake, and milk production was reduced by about 0.27 despite higher OMD and apparently more efficient energy use. On the other hand, there may be practical advantages for dairy farmers if water does not have to be supplied to all paddocks, or areas within paddocks, being grazed.

An alternative is to make water freely available only at milking time(s), a policy that was examined by Cowan *et al.* (1978) in the Atherton Tablelands of northern Queensland when mean maximum temperature was 27°C and mean relative humidity was 79%. A group of Friesian cows with an average milk yield of 11.4 kg/d (range 8.4–14.9 kg/d) was given access to water only before each milking, for periods of 20 minutes twice daily. Compared with the performance of cows given continuous access to water at pasture and at milking times, restriction of access reduced the amounts drunk by 15% and had no effect on milk composition. An effect of the restriction on milk yield, a reduction of about 5%, was evident only during the two days after this treatment was imposed. Cowan *et al.* (1978) suggest that there might be no important effect on the production of cows in this environment if they were consistently provided with abundant water only at milking times, implying they could adapt to this management, but if they were

moved among paddocks that did not all have a water supply then the recurring adjustment to deprivation might have a significant cumulative effect on lactation yield.

King and Stockdale (1981) made a similar type of study with Jersey × Friesian crossbred dairy cows in northern Victoria; their mean milk yield was about 13 kg/d. During a 10-day period with high temperatures, 33.7°C mean maximum, the cows were given free access to water, or access for 20 minutes twice daily before milking, or for 20 minutes before the evening milking only. Compared with free access, twice-daily watering did not significantly affect feed intake, milk production or live weight although water intake was reduced from 67 to 45 l/d. With once-daily access there was a similar reduction in average daily water consumption, but it was considerably lower during the first four days of the treatment than during the remaining six days. Feed intake, milk yield and live weights were all significantly reduced during these four days but subsequently increased so that over the whole 10 day period they did not differ from the other two treatments. These results, like those of Cowan *et al.* (1978) are evidence that cows can adapt to restrictions on access to water, and King and Stockdale (1981) concluded that it need not be supplied in all pastures. They suggested this might not be so for cows with higher milk yields (i.e. more than 13 kg/d) or if they were consuming dry supplementary feeds, and it should be noted the experiment was made only for a 10-day period.

Trough size and flow rate

Especially when dairy cows are provided with water only at milking times, it is important that the length of water troughs and the size of pipes for replenishment are sufficient to allow a large number of animals to satisfy their thirst during a period that might be less than 1 h. MAFF (1981) provides information on these matters. It suggests that cows require a 450 mm length of drinking space and that they will drink at rates up to 14 l/min. A single drink of 67 l by a cow as reported by Cowan *et al.* (1978) might be unusual, but if each cow in a herd of 100 were to spend 4 min drinking 30 l during the course of a 0.5 h period of access then the minimum effective trough length (i.e. excluding the 0.2 m approximately occupied by each ball valve assembly) would have to be about 7 m with a water supply at the rate of 100 l/min. Even with good water pressure, the flow through a 25 mm supply pipe would be only about 14 l/min. At the same pressure, doubling pipe diameter can give about a six-fold increase in flow, but rate of entry to the trough may be restricted by the size of the orifice in the ball valve assembly. With a 3 m head of water, the flow through a 10 mm orifice is about 25 l/min. If water were provided in large round troughs containing 1000 l or more, the rate of replenishment could be less than that required for shallow troughs. Individual water bowls operate at relatively low pressures and require correspondingly larger diameter supply pipes; cows drink from these at rates up to 5 l/min. The lip of a trough or bowl used by cattle other than young calves should be about 0.9 m above ground level so that they can drink in comfort and fouling of the water is minimised.

Spatial distribution

Sheep and cattle in small paddocks may drink several times in 24 h, but as the area served by one watering point increases the time required to walk to water from grazing and return becomes longer and drinking frequency will decrease (Squires and Wilson 1971). The optimum distances between points will be compromises determined by the costs of their establishment

and expected returns from the livestock; by the intrinsic stock-carrying capacity of the rangeland and its resistance to degradation of soil and vegetation; the type of animal and the distance that it will walk to feed; and the frequency of drinking made necessary by climatic conditions and type of vegetation. The siting of watering points can be used to manage livestock distribution and obtain more even use of pasture (Ganskopp 2001).

Sheep grazing *Atriplex* spp. communities commonly need to drink twice daily, especially in summer, so that their effective grazing range is about 2.5 km radius (Osborn *et al.* 1932; Squires 1976). Squires (1970, 1976) observed that lambs will usually walk these distances with their mothers, but when breeding ewes and wethers were provided with only salty feed, at a distance of about 4.5 km from water the frequency of drinks decreased to three in two days, or once daily, and their feed intakes and productivity decreased. Sheep grazing semi-arid grassland (non-salty diet) have been observed to range more than 5 km from water, drinking only every third day or after even longer intervals in winter, but drinking daily when temperatures exceeded 41°C (Alexander and Lynch 1973).

Schmidt (1969) observed the behaviour of Shorthorn cattle during the dry season on the Barkly Tablelands (north-west Queensland) where little shade is available. He classified his cattle as 'walkers' and 'non-walkers'. Both types drank once daily but the non-walkers grazed the poorer-quality pastures close to the watering points and walked a maximum distance of 9.6 km/d whereas the walkers travelled up to 16 km/d in order to graze better-quality pastures further away. There appeared to be no difference in performance between the two types except that there was a greater proportion of walker cows without calves (39%) than non-walkers (19%).

Low *et al.* (1978) observed British breeds of cattle in central Australia, grazing in a 153 km^2 paddock containing mixed wooded and open grazing land. In summer, when the maximum temperature was 41°C, 90% of the herd came in to water each day but in winter, when the maximum temperature was 23°C, only 34% of the herd came in. The study also showed that watering frequency was influenced by forage location and phenological state. With abundant green forage (water content 0.6–0.7) the cattle did not have to graze far from the watering points and drank nearly every day. The frequency of watering dropped as the pastures dried off (water content 0.3–0.4) and the cattle had to walk farther to graze. Additional observations on areas up to 1800 km^2 (Low *et al.* 1978) also showed that the distance cattle travelled was influenced by forage availability and preference. When grazing conditions were favourable the majority of cattle grazed 0.5–8.0 km away from water, but when the forage was sparse and dry they grazed as far as 10–14 km away. Some travelled even greater distances to forage and this behaviour was usually associated with a reduction in the drinking frequency. In one instance, cattle were observed grazing 24 km from the nearest water.

These and other observations of the behaviour of sheep and cattle in the pastoral zone assist decisions on desirable locations for, and distances between, watering points. An area of rangeland might be able to support one cattle beast, or five sheep, per five hectares if uniformly grazed; thus, if watering points were 8 km apart each point would serve about 5000 ha and would be used by 1000 cattle or 5000 sheep. In fact, rangelands are not grazed uniformly, the extent of use decreasing with distances from water beyond about 1 km; the area of land within this radius, about 300 ha, would be denuded of vegetation and grossly degraded if it was the centre for such large numbers of livestock. Generally it is advisable that one watering point should serve about one-third of those numbers, say 300 cattle or 1500 sheep. If established 5 km apart, each point will serve about 2000 ha and it may be noted that a 40 kg sheep walking, on level ground, 2.5 km

to and from water twice daily would expend about 1.5 MJ of ME per day on this activity (see Chapter 1).

Allowances

The estimates of water allowances (Table 5.6) are based on the information reviewed in earlier sections, especially that on water turnovers (see, p. 190) and the report of Winchester and Morris (1956) that has been used to distinguish between *B. taurus* and *B. indicus*. The estimates should be regarded as guidelines. Like those given by the ARC (1980), they may tend towards generosity and lesser amounts of water could be provided if it had to be carted to stock. The allowances are related to DM intakes, as calculated for desired animal performance (Chapter 1) or predicted (Chapter 6). It would generally be advisable to provide at least those allowances, especially in hot environments because of the crucial importance of an adequate water intake for effective thermoregulation, although animals grazing moist pasture at T_a of, say, 20°C or less may not have to gain more than about 20% of their water needs by drinking. The majority will have to be drunk by animals given dry diets, in any T_a, and by those grazing dry pastures. When planning for water supplies, in addition to ensuring adequate availability (see, p. 200), allowance should be made for wastage and losses by evaporation. Rates of evaporation from a free-water surface exceed 2500 mm per annum in about 75% of Australian locations, varying from about 900 mm/yr in south-west Tasmania to 4500 mm/yr in arid areas (Anon. 1977–1978). Consequently the levels in dams or open storages will fall, on average, by 2.5 m/yr in addition to draw-off unless replenished.

Table 5.6. Estimates of total water allowances (drunk and in feed) for cattle and sheep at various mean environmental temperatures (T_a), expressed as litres per kilogram dry matter intake (DMI)

	Mean T_a (°C)				
	≤15	**20**	**25**	**30**	**35**
Allowances, litres per kg DMI					
Weaned cattle:					
B. taurus breeds	3.5	4.0	5.5	7.5	10.0
B. indicus breeds	3.0	3.5	4.5	6.0	8.0
Calves	6–8		9+		
Weaned sheep	2.0	2.5	3.5	5.0	7.0
Lambs	5–7		8+		
Pregnancy	(cattle last four months, sheep last two months) Increase allowances by 30%.				
Lactation	Increase allowances by 1 litre per kg milk produced.				

(Values are for drinking water containing not more than 2000 mg total soluble salts per litre (2000 ppm) and feed containing not more than 100 g ash (other than soil ash) per kg dry matter; see text for adjustments of allowances when water and feeds contain higher concentrations of electrolytes.)

The allowances given in Table 5.6 are varied with mean daily T_a, that is (minimum + maximum)/2. Other publications on the relation between water needs and environmental temperature have generally not described how the latter variable is to be defined in practical

conditions, but Winchester and Morris (1956) found that the water intakes (l/kg DM) by cattle kept outdoors in temperatures varying from 14–50°C with a mean of 32°C were similar to those of similar animals kept in climate chambers at near-constant 32°C.

The allowances are applicable for water containing not more than about 2000 mg TSS/l provided to animals given feeds, other than those treated with alkali, with not more than 100 g ash/kg DM (excluding ash contributed by contamination with soil). From the information reviewed on p. 188, the following assumptions may be made:

Water. For each 1000 mg TSS/l in excess of 2000 mg/l, allowances for sheep increased by 3% and for cattle increased by 6%.

Feed. For each 10 g ash per kg DM in excess of 100 g/kg, allowances for sheep increased by 5% and for cattle increased by 10%.

When treated with caustic soda, if at the rate of 50 g/kg DM, then water consumption will be increased by at least 2 l (sheep) or 4 l (cattle) for each kg of this feed eaten.

During the last two months (sheep) or four months (cattle) of the gestation period, and during lactation, increase the allowances (Table 5.6) by 30%. During lactation, in addition, increase the allowances by 1 litre per kg milk produced.

Chapter 6

Prediction of feed intake

Summary

In the management of hand-fed ruminants, it is necessary to know their voluntary intake of feed merely to ensure that they are able to consume a formulated diet. However, production from grazing animals is determined primarily by their voluntary intake and estimates of their requirements for a target level of production must start with this information. A system is presented for predicting feed intake as the product of two factors, the potential intake of feed by the animal and the relative intake offered by the feed or the pasture. Potential intake depends on the mature size of the animal (its Standard Reference Weight, SRW; see p. 34), its current size as a proportion of SRW, and its energy demand; but may be reduced by disease or thermal stress. Relative intake is a function of the feed quality and, for grazing animals, the quantity of herbage available.

At pasture, the prediction of relative intake is complicated by the heterogeneity of the sward and the system described attempts to simulate selective grazing behaviour. The quantity of herbage available is viewed as being distributed between a number of quality pools and it is assumed that an animal attempts to satisfy its potential intake from each of these pools in succession, starting with the highest quality. The extent to which it will eat herbage of progressively lower quality depends on the weight of herbage in each pool and the unsatisfied potential intake at that point. Relative intake represents the sum of the values for each pool.

Supplementary feeds may increase the intake of a roughage or a pasture that offers a diet deficient in nitrogen (or some mineral nutrients) but, more usually, the supplement will depress the intake of the basal diet. The appropriate level of substitution is estimated by incorporating the supplement into the calculation of relative intake, according to the composition and amount of the supplement and the energy demand of the animal.

Examples of feed intakes for several classes of livestock are tabulated, but these estimates are of limited value for grazing animals because of variation in diet selection and herbage availability; predictions for a particular pasture are more easily made with a computer program. The system described in this chapter has been combined with other recommendations in this Report into the GrazFeed program that allows the user to assess the animal production obtainable from a specified pasture and the likely response to supplementation.

Introduction

The aim of this chapter is to indicate the factors that determine the intake of feed by sheep and cattle and to present what information we have on the appropriate mathematical functions that

may be used to predict feed intake. Most of the schemes developed in other feeding standard systems are applicable only to housed or other hand-fed animals. Under these conditions, the main reason for wanting to know how much feed a ruminant can eat is to ensure that a formulated diet is within the animal's capacity. In Australia, this is of interest mainly for lot-fed animals and some dairy cattle. Most other ruminants are rarely housed and subsist very largely on grazed pasture, with supplements offered only at times of severe feed shortage. For these animals, the voluntary intake of feed while grazing is the main determinant of their productivity and the estimation of their nutrient requirements must start with this information.

The earlier Report (SCA 1990) described a system for predicting feed intake as the product of two factors, the potential intake of feed by the animal and the relative intake offered by the feed or the pasture. Potential intake depends on attributes of the animal but may be reduced by disease or thermal stress. Relative intake is a function of the quality and availability of the feed and defines the proportion of its potential intake that an animal can achieve in a specified situation. At pasture, the prediction of relative intake is complicated by the heterogeneity of the sward and the system attempts to simulate selective grazing behaviour. The quantity of herbage available is viewed as being distributed between a number of quality pools and it is assumed that an animal attempts to satisfy its potential intake from each of these pools in succession, starting with the highest quality. The extent to which it will eat herbage of progressively lower quality depends on the weight of herbage in each pool and the unsatisfied potential intake at that point. Relative intake represents the sum of the values for each class.

Supplementary feeds may increase the intake of a roughage or a pasture that offers a diet deficient in nitrogen (or some mineral nutrients) but, more usually, the supplement will depress the intake of the basal diet. By incorporating the supplement into the calculation of relative intake, according to the composition and amount of the supplement and the energy demand of the animal, the appropriate level of substitution may be estimated.

Examples of feed intakes for several classes of livestock are tabulated later in this chapter but, as relative intake varies with each particular grazing situation, the prediction of intake is more easily done with the computer program GrazFeed® (Freer *et al.* 1997, 2006; Horizon Agriculture Pty Ltd, PO Box 598, Roseville NSW 2069, Australia). GrazFeed was developed alongside the earlier Report as a simple way of implementing its recommendations for predicting feed intake and requirements for energy and protein. The program has been widely used in southern Australia as a decision support tool for the nutritional management of sheep and cattle. Its use in practice and more recent research have revealed the need for modifications and amendments to the functions in GrazFeed (Freer *et al.* 2006) and these have been incorporated in this chapter and in Chapters 1 and 2 of this Report. The earlier conclusion that, in the absence of better information, the functions for predicting feed intake by sheep can be applied to goats under similar grazing conditions remains unchanged (AFRC 1998; NRC 2006).

Although many models have been developed for estimating the voluntary feed intake by housed animals, there are few other practical tools available that attempt to base these estimates on the predicted diet eaten by grazing animals. One of these is the NUTBAL program (Stuth *et al.* 1999), which uses a different approach for estimating diet selection and is mentioned on p. 216.

Factors affecting intake

The factors affecting intake can be conveniently grouped under two headings.

(*a*) The potential intake of feed by the animal

This is defined as the amount of feed eaten when the animal is offered abundant feed and is able to select a diet with a dry matter digestibility of at least 0.8 or a M/D value of at least 11 MJ ME/kg DM. The mean potential intake of feed by a group of animals is determined by their body size and physiological state. This potential may, however, be reduced by disease or thermal stress.

(*b*) The relative intake offered by the pasture

This expresses the proportion of its potential intake that the animal can be expected to achieve under the existing conditions of grazing or from the particular feed that is offered. In general, it is a function of two factors: the extent to which the chemical composition of the selected diet restricts its intake and the physical features of the sward that limit the animal's ability to harvest herbage in the time available for grazing.

The actual intake of feed is then calculated as the product of potential and relative intakes; for example, if the predicted potential intake by a sheep is 1.6 kg DM/d but feed conditions restrict relative intake to 0.7 (on a scale of 0–1), the predicted intake is 1.12 kg DM/d. For housed animals, this calculation is a simple procedure because relative intake is merely a function of the composition of the diet, a stable attribute that can readily be measured. At pasture, the estimation of relative intake is much more difficult. At any one time, the sward is a heterogeneous collection of plant components of different nutritive value and the amount and quality of these components is continually changing through growth and maturation. This means that, to estimate relative intake, one must first describe the sward in quantitative terms and then predict both the effect of the spatial distribution of the plant components on the animals' ability to harvest them and the effect of selective grazing on the quality of the diet.

Potential intake

Size of animal and its relationship to weight

An upper limit to the voluntary intake of feed is set by some combination of the animal's potential demand for energy and its physical capacity for feed, both of which are clearly proportional, in a general way, to the size of the animal. However, current weight is clearly not a useful predictor of body size as it is confounded with stage of development and body condition.

The approach used here is to predict potential intake from two variables: (*i*) the Standard Reference Weight, SRW, of the animal (i.e. the weight of the animal when it reaches mature skeletal size and has a condition score in the middle of the range (see Chapter 1); and (*ii*) the current size of the animal relative to its mature size. Relative size is estimated as the ratio of 'normal' weight to Standard Reference Weight. The upper limit to the normal weight, *N*, of the growing animal, i.e. its weight when its condition score is in the middle of the range, follows a pattern with time (equation 6.1) similar to that described by Brody (1945), with the allometric scaling of the time constant for skeletal development from Taylor (1968).

$$N = A - (A - \mathrm{B}) \exp(-k\, T\, A^{-0.27}) \qquad (6.1)$$

where:

A = SRW (kg),
B = the birth weight (kg),
T = the age of the animal (months),
k = 0.47 for sheep and 0.35 for cattle.

In animals with interrupted growth, frame size, and hence, normal weight may increase slowly, i.e. with a smaller value for k, even though the animal either fails to gain weight or loses weight. In the GrazFeed model, the rate parameter falls to a minimum when daily gain is less than 40% of the gain computed from the differential of equation 6.1.

The relative size, Z, of the animal is then calculated as the ratio of normal weight to SRW, a ratio that cannot exceed 1.0 (when skeletal maturity is reached), and its relative condition, RC, is calculated as the ratio of current live weight, W, to normal weight. It follows that current weight can be regarded as the product of SRW, relative size and relative condition (equation 6.2).

$$W = A\ (W/N)(N/A) \tag{6.2}$$

Using values of A and Z estimated in the way described above, equation 6.3 (Fig. 6.1) should adequately predict the potential intake, I (kg DM/d), of feed by a weaned animal while it is not lactating and is within its thermoneutral zone. This equation implies that potential intake reaches a peak when the relative size of the animal is 0.85 (Graham and Searle 1972). For RC >1.0, potential intake is depressed (see Fox 1987) by multiplying I by a condition factor, CF, (equation 6.4) for non-lactating animals.

$$I = j\ A\ Z(1.7 - Z)\ \text{CF} \tag{6.3}$$

where:
j has suggested values of 0.040 for sheep and 0.025 for cattle.

$$CF = RC\ (1.5 - RC)/0.5 \text{ for } RC > 1.0, \text{ otherwise } CF = 1.0 \tag{6.4}$$

Equation 6.3 was developed empirically from a wide range of data and its predictions for mature animals in normal condition are similar to those of ARC (1980). Although predictions for immature animals are greater than those of ARC (1980), they are in general agreement with the results of Langlands (1972, 1973), Allden (1979) and Weston (1980). The main weakness of the ARC system is that potential intake is simply a function of $W^{0.75}$, regardless of the mature weight of the animal in question or its body condition. Thus a young animal of high SRW may be indistinguishable from a mature animal in poor condition or a mature animal of low SRW. The same weakness is in the French (Jarrige 1989) and USA (NRC 1996) systems; both base their prediction of feed intake on $W^{0.75}$ regardless of the degree of maturity of the animal, although the American system does make adjustments for three categories of frame size and for high body condition. Additionally, the use of 0.75 as the exponent for W is questionable, as Blaxter *et al.* (1966*b*) and Frisch and Vercoe (1977) showed that 0.75 was inferior to 1.0 as the exponent for comparing breeds of sheep or cattle.

An examination of how the prediction of potential intake from equation 6.3 varies with any specified values of A, Z and RC may be made by using the spreadsheet programs SheepExplorer and CattleExplorer that are available at www.pi.csiro.au/grazplan.

The model allows immature animals recovering from a period of undernutrition to exhibit compensatory weight gain. In such animals relative size slowly increases during undernutrition (see above), despite a fall in W, so that when food becomes plentiful the difference between the potential intake predicted from Z and the maintenance requirement predicted from W (see Chapter 1) will be greater than for a well-nourished animal of the same relative size.

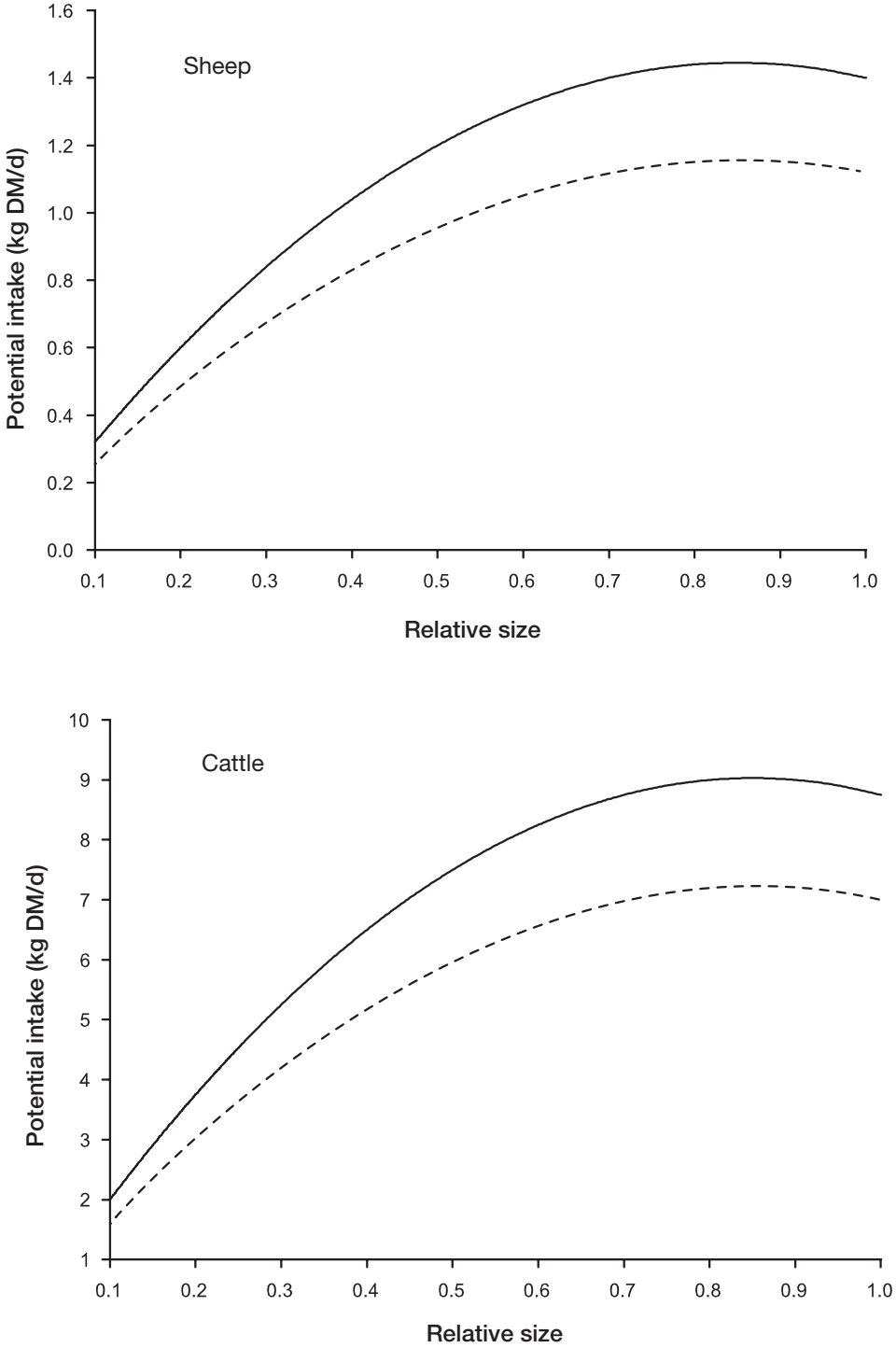


Fig. 6.1. Predicted potential intake of sheep with SRW = 50 kg (solid line) or 40 kg (dashed line) and cattle with SRW = 500 kg (solid line) or 400 kg (dashed line) in relation to relative size for animals with relative condition ≤1.0 (from Freer 2002).

Physiological state of the animal

Pregnancy

The development of the conceptus involves an exponential increase in the additional energy demand of the pregnant animal (Chapter 1), but there is no evidence for an increase in the voluntary intake of food (Weston 1982). Forbes (1971) suggested that the space occupied by the conceptus in the body cavity restricts the capacity of the reticulo-rumen to such an extent that, far from increasing, intake is maintained only by a decrease in the mean retention time of digesta in the gut (Graham and Williams 1962; Faichney and White 1980). The decline in intake that is commonly observed a few days before parturition is probably related to endocrinological changes (Forbes 1971).

Lactation

Work reviewed by the ARC (1980) shows that the potential intake of roughage diets by cows and sheep increases by up to 60% during lactation. The size of the increase depends on the time from parturition and the number of young. Increase in intake lags behind the increase in milk yield and does not reach a peak or plateau until about four months after calving or about 1.5 months after lambing.

These conclusions are in agreement with the results of Davies (1963), and Corbett (1968) and others reviewed by Treacher and Caja (2002). For modelling, it is more satisfactory to predict the changes in intake on a continuous basis, rather than from tables of monthly values. The general form of the relationship between intake and time is similar to that of the lactation curve (Wood 1969). A re-formulated version of this function (equation 6.5) calculates the factor m, which is used as a multiplier on the right hand side of equation 6.3 when predicting the intake of food by lactating animals. The effect of this is shown in Fig. 6.2.

$$m = 1.0 + aM^b \exp(b(1-M))L.D \tag{6.5}$$

where:

$M = T/c$,

T = day of lactation,

c = time of peak potential intake (d),

L scales m for body condition at parturition (ewes and beef cows) or for peak milk yield (dairy cows) [see below for method of calculating L],

D is a function of the ratio of actual to potential milk yield. Chapter 1 sets out the way in which milk yield responds to current nutrition, a response that is reflected in the value of m.

For ewes and beef cattle, the scalar L is calculated as 0.5 + 0.5⋆relative condition at parturition. For dairy cattle, L has a value of 1.0 for a lactation with a peak milk yield equivalent to $0.05A$ kg FCM/day, where A is the SRW of the cow. For a different peak yield Y, the value of L is calculated from equation 6.6; a much larger effect than that suggested by ARC (1980) but supported by results of Wales *et al.* (1999) and Beever *et al.* (2001).

$$L = 1 + 0.6\,(Y - 0.05A)/\,0.05A \tag{6.6}$$

Values of parameters a, b and c, designed to match a range of data, are shown below.

		No. young suckled	*a*	*b*	*c* (d)
Ewes	Merino type	1	0.52	1.4	28
		2	0.71	1.4	28
	Meat type	1	0.66	1.4	28
		2	0.88	1.4	28
Cows	Beef type	0	0.42	1.7	62
		1	0.42	1.7	62
	Dairy type	0	0.85	0.7	81
		1	0.58	0.7	81

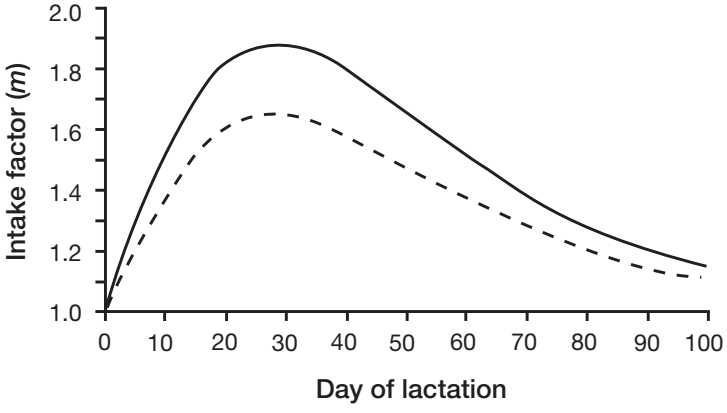


Fig. 6.2. The multiplier factor m for potential intake of feed by lactating ewes with twin lambs (solid line) or single lambs (dashed line).

Unweaned young

The potential intake of pasture by unweaned lambs and calves in the first few weeks of life depends on rumen development rather than body weight. The appropriate proportion, *p*, of potential intake is calculated from equation 6.7 (illustrated in Fig. 6.4) and the value of *p* is used as a multiplier in equation 6.3.

$$p = (1.0 - P_{milk})/[1.0 + \exp(-a(T - X))] \quad (6.7)$$

where:
P_{milk} = proportion of the diet from milk,
T = days from birth,
X = 25 days for lambs and 60 for calves,
a = 0.5 for lambs and 0.22 for calves.

Disease and climatic factors

Diseases reduce the potential intake of the animal and parasitic infestations are of particular relevance to grazing animals. Tests with different intestinal parasites indicate a complex pattern of responses depending on the level of infection and the development of resistance (Steel and

Symons 1979; Coop and Sykes 2002). As a result, it is not possible at present to make quantitative predictions.

Climatic factors leading to thermal stress in the animal will also affect voluntary food intake, but the response will depend on the extent of insulation and level of metabolic activity of the animal and on the quality of the diet. Indoor studies show a consistent increase or decrease in food intake as the ambient temperature falls or rises, respectively, beyond the thermal neutral zone of the particular animal (see Chapter 1). However, there are few results obtained under grazing conditions, where the flexibility of grazing behaviour allows animals to mitigate the effects of climatic extremes by seeking shade or shelter. Reviews by Weston (1982; 2002) and the NRC (1981*a*) indicate that while the effects may be large, it is difficult to make predictions for grazing animals. The adjustment for high temperatures that is used in the GrazFeed program operates when the average daily temperature exceeds 25°C and the night temperature exceeds 22°C. The potential intake of herbage by cattle, other than Brahman types, is then reduced by 2% for each rise of 1°C in average daily temperature (Fox 1987); for other stock the reduction is 1% per °C. If the ambient temperature falls below the animal's lower critical temperature (see p. 27) potential intake is increased by 1% per °C (Fox 1987); an effect that is reduced with rainfall, to disappear at 20 mm per day.

Relative intake

Relative intake or the proportion of the potential intake that can be satisfied from a grazed pasture is the product of two factors: the extent to which the chemical composition of the herbage restricts its intake (relative ingestibility), and the physical features of the sward that limit the animal's ability to harvest herbage in the time it has available for grazing (relative availability). If a pasture were a homogeneous mass of plant material with single values for these chemical and physical characteristics, relative intake would be simply the product of the two. But this is far from being the case, and the predicting process must simulate selective grazing in a heterogeneous sward and the effect of this on nutrient intake.

Herbage quality

A number of reviews (e.g. Balch and Campling 1962; Freer 1981; Minson 1982*b*; Weston 2002) have indicated that, within an upper limit set by the energy demand of the animal, the main characteristics of plant material that determine its intake by ruminants are those that limit the rate at which it can pass through the gut. The construction and testing of models that simulate the rates of digestion and passage of digesta, as functions of the physical and chemical composition of the diet, is an active field of research (e.g. Mertens 1996). A sub-model of this type will eventually be a basic component of any model of feed intake but the level of precision achieved so far is inadequate for grazing animals, with the difficulty of relating the predicting variables to measurable features of the sward.

However, the pasture characteristics that determine the disappearance of digesta from the gut are crudely reflected in the overall apparent digestibility (or metabolisability) of the diet, a much more readily estimated characteristic. Several reviews (e.g. Hodgson 1977; Freer 1981) have demonstrated linear relationships between apparent digestibility and voluntary intake over the full range of maturity to be found in pasture plants, up to M/D values of at least 11 MJ/kg DM. For a 50 kg sheep, voluntary intake increases at about 20–25 g DM per unit increase in

digestibility and the relationship appears to be proportionately the same for cattle (Hodgson 1977). Suggestions, from earlier reviews, of curvilinearity in the relationship stem mainly from the inclusion of milled roughages and diets containing a high proportion of grain or other foods of low fibre content. For example, in the US system for predicting feed intake by lot-fed beef cattle (NRC 1996), predicted dry matter intake reaches a peak for a diet of about 9 MJ ME/kg, a sharp contrast with results from herbage diets.

The estimation of relative ingestibility (*RQ*) for temperate grasses (C3) and legume species (equation 6.8) is based on results reviewed by Freer (1981) and local results (Freer and Jones 1984). Measurements made with tropical (C4) pasture grasses (Minson 1982*b*; D. B. Coates pers. comm.; S. R. McClennan pers. comm.) indicate that, although their digestibility is commonly about 15 percentage units lower than that of C3 species at the same stage of maturity, voluntary intake is correspondingly higher at the same digestibility. Coates' data show a strong relationship ($R^2 = 0.81$) between DMD and DMI for a number of tropical grasses: the same slope but an increase of 0.26 in the intercept compared with C3 grasses. The difference is expressed in the value of *g* in equation 6.8.

$$RQ = 1 - 1.7(\max((0.8 - (1 - P_{legume})g) - D), 0.0) \quad (6.8)$$

where:

P_{legume} = the proportion of legume in the pasture,

D = the DMD of the selected diet,

g = 0.00 for C3 grasses or 0.16 for C4 grasses.

Herbage weight and sward structure

In the case of a housed animal or for a sheep grazing a pasture containing at least 2 tonnes herbage DM/ha (about 3 t DM/ha for cattle), the intake of feed is determined solely by the factors so far considered: potential intake and the quality of the selected diet. However, to the extent that the weight of herbage in the pasture falls below this, it becomes progressively more difficult for the grazing animal to satisfy its potential intake in the time that it can spend on this activity in each day. There are numerous research models that explore a detailed mechanistic analysis of the grazing process through simulation of bite size and frequency in relation to sward structure (e.g. Baumont *et al.* 2004). Although at present they require a specification of the sward that is too detailed for practical application, such models may have a useful role in the future.

On the other hand, a simple exponential relationship between relative availability, *F*, and the weight of herbage, *B*, results from the assumption that each increment of change in intake with respect to herbage weight is proportional to the unsatisfied appetite at that level of herbage:

$$dF/dB = 1 - F$$

It follows that:

$$F = 1 - \exp(-aB)$$

with *a* as the rate constant, an equation that is similar in its general form to many experimental observations (Arnold and Dudzinski 1967; McKinney *et al.* 1970; Langlands and Bennett 1973). The parameter *a* varies with sward structure and animal type and intake prediction needs to account for the interactions between sward density and the process of grazing, expressed in the

rate of eating (g/min) and the time spent grazing (min/d). The model expresses these variables as relative values, i.e. as proportions of the values that they would have if the supply of feed were sufficiently great that it did not limit intake. The results of Allden and Whittaker (1970) suggest that the relationship between relative availability, F, and the combination of relative rate of eating, E, and relative time spent eating, T, can be expressed in functions of the general form shown in equation 6.9.

$$F = E.T = (1.0 - \exp(-bB))(1.0 + c\exp(-dB^2)) \quad (6.9)$$

where the values of b, c and d vary with the density of the sward (see below).

When abundant pasture is present, both E and T have a value of 1.0. If the weight of herbage falls, E decreases and T increases and compensation may be complete for a time. But although E may decrease, ultimately to zero and often to a quarter of its maximum value, T will not even double before it reaches a ceiling, with the result that the product, relative availability, is progressively reduced as pasture mass declines (Fig. 6.3).

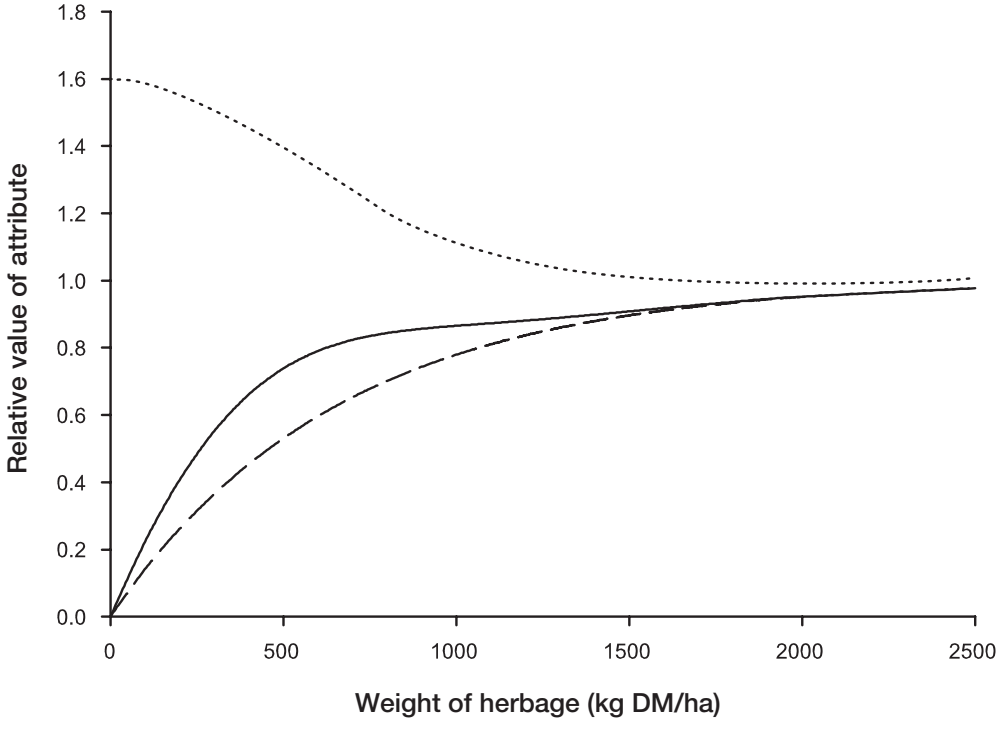


Fig. 6.3. Relative availability and its component attributes, for sheep (for the first herbage class where the unsatisfied appetite of the animal has a relative value of 1), in relation to the weight of herbage dry matter. The dotted line represents the relative time spent grazing, the dashed line indicates the relative rate of eating, and the solid line is the product, relative availability (from Freer 2002).

Herbage classification methods and the simulation of selective grazing

In applying the above factors to the prediction of relative intake, it is not enough to treat the pasture as if it were a single mass of material of known weight and quality. Grazing animals

select living rather than dead material, younger rather than older, and leaf rather than stem (Arnold 1970). If the selection process is to be simulated, the herbage in the sward must be classified in a way that corresponds to that in which it is perceived and eaten by the grazing animal. In the GrazFeed model, the herbage is distributed between six pools, each of which has a fixed digestibility (0.8 to 0.3). It is assumed that the animal attempts to satisfy its potential intake from each of these pools in succession, starting with the most digestible class. The extent to which this can be done depends on both the weight and digestibility of herbage in each pool. The higher the proportion of the potential intake that is satisfied from any pool, the less the animal will attempt to eat from the next lower pool, and so on. The overall relative intake is the sum of the relative intakes achieved from each pool.

The function for calculating the relative availability in each pool, F_d (equation 6.10) is applied to each pool in turn, starting with the most digestible. UC_d represents the proportion of potential intake left unsatisfied by material selected earlier in the sequence. The exponents in equations 6.11 and 6.12, which predict the relative rate of eating and the relative time spent eating for pool d, increase with the proportion of the herbage that is in that pool (ϕ_d). Also, if the sward is shorter or taller than an assumed mean value of 3 cm/t DM/ha, then the ratio of its height to the default height, HR_d, decreases or increases, respectively, the availability of the herbage at a particular weight. The parameters used in these equations are for herbage weights (B, t DM/ha) that represent material cut close to ground level with a shearing hand-piece.

It is not assumed that legume herbage is selected in preference to grass as the evidence for this is quite equivocal (see NRC 2006 for a detailed discussion), but its presence in the sward increases the relative ingestibility of the feed, up to a maximum of 17% (Freer and Jones 1984). However, in the computation of relative intake for pool d, R_d, by the multiplication of F_d and RQ_d, the effect of the proportion of legume in the pasture decreases as herbage availability declines (equation 6.13).

An example of the calculation of relative intake is shown in Table 6.1. The relative availability from the first pool reduces the unsatisfied capacity, UC, of the animal to eat from the second class and therefore the value of F calculated for the second pool is multiplied by the new value of UC. This process continues until all pools have been considered or the relative capacity of the animal has been satisfied. Each of the pool values for relative availability is multiplied by the appropriate RQ to give the relative intake, RI, of herbage from that pool. The cumulative relative intake achieved from all pools is multiplied by the potential intake to give the actual intake of herbage dry matter. The digestibility of the diet is calculated from the contributions of the different pools to the diet. Fig. 6.4 shows the predicted effect of both B and D on the intake of food dry matter and Fig. 6.5 illustrates the direct effect of B on the ability of the animals to select a diet of higher digestibility than the mean of the material on offer.

$$F_d = UC_d RR_d RT_d \text{ where } d = 1 \ldots 6 \tag{6.10}$$

where:

$$UC_d = \max\left(0, 1 - \sum_{k=1}^{d-1} F_k\right)$$

$$RR_d = 1 - \exp(-(1 + 0.35\phi_d)a\, HF_d\, B_d) \tag{6.11}$$

$$RT_d = 1 + 0.6\exp(-(1 + 0.35\phi_d)(b\, HF_d\, B_d)^2) \tag{6.12}$$

$$HF_d = 0.2 + 0.8HR_d$$

a = 1.12 for sheep; 0.78 for cattle,
b = 1.12 for sheep; 0.74 for cattle.

$$R_d = F_d RQ_d \left(1 + 0.17 \left(\sum_{d=1}^{6} F_d \right)^2 P_{legume} \right) \quad (6.13)$$

This method of predicting relative intake depends on the assumption that the weight of herbage will remain almost constant over the period to which the estimate applies. For a once-daily prediction in a continuous grazing system, this is likely to be true, but for intensive rotational systems, where a significant proportion of the herbage may be eaten within one day, it is necessary for the model to repeat the calculations several times during each day. The GrazFeed model calculates relative intake five times each day, with the weight of available herbage at each time being reduced by the amount already eaten and by the amount that has been trampled or fouled by the animals. The latter weight has been provisionally set at 100% of the amount eaten, a level indicated by intake measurements of Wales *et al.* (1998) from intensively strip-grazed dairy cows.

In semi-arid grazing lands, where vegetation heterogeneity is extreme and plant cover incomplete or patchy, the functions presented here for selective grazing would be inappropriate. The most promising alternative for predicting the digestibility of the selected diet is through the analysis by near infrared reflectance spectroscopy (NIRS) of faecal samples from grazing animals, calibrated against standards of known *in vivo* digestibility (Coates 1999). This approach is used in the NUTBAL model (Stuth *et al.* 1999) to predict relative ingestibility. However, some estimate of the relative availability of the feed base is still required for the prediction of relative intake.

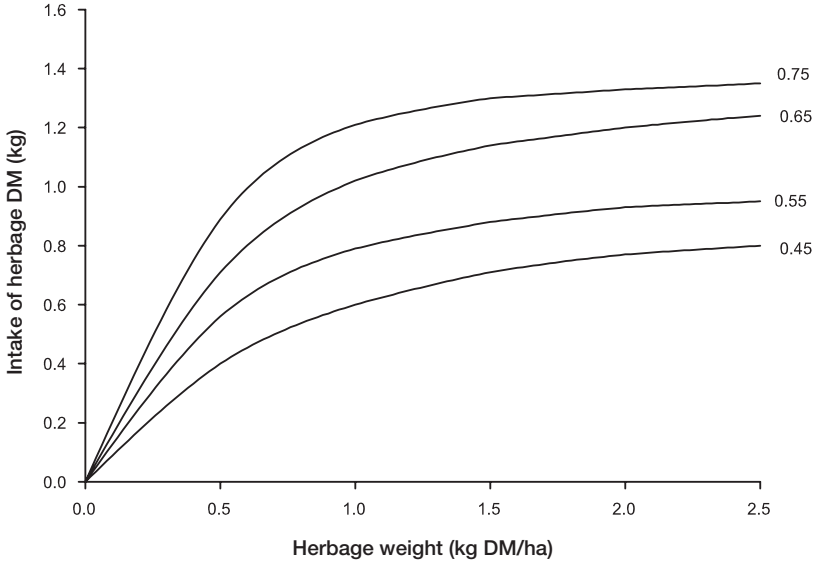


Fig. 6.4. Predicted intakes of herbage by sheep (SRW 50 kg) grazing temperate grass pastures differing in mean digestibility of available herbage.

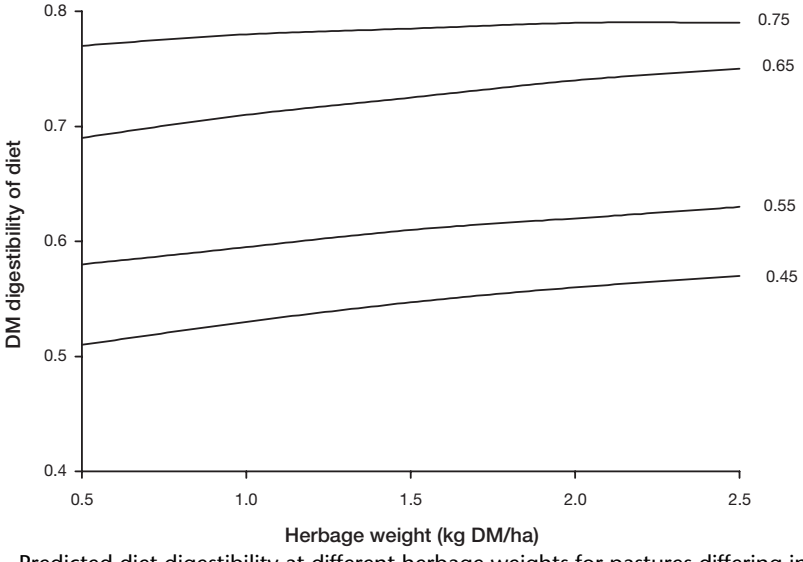


Fig. 6.5. Predicted diet digestibility at different herbage weights for pastures differing in mean digestibility.

Limitations set by protein and mineral contents of the diet

The intake of herbage may be depressed if the diet is deficient in certain chemical constituents, particularly those that are essential nutrients for the rumen microbial population, and most commonly nitrogen. The requirement of rumen degradable protein (RDP) from most feeds for microbial synthesis ranges between about 7 and 11 g/MJ of ME intake (see Table 2.5). If the concentration of RDP in the herbage is insufficient to supply the required amount, then the intake of feed will fall. Quantitative details on this effect are sketchy but the procedure adopted in the GrazFeed model is to reduce the predicted potential intake in proportion to the deficit of RDP, i.e. by multiplying it by the ratio of the intake to the requirement of RDP. Doing this will not of course increase this ratio but the assumption is made that recycling of urea to the rumen (Nolan 1981) will offset the remaining deficiency of RDP.

Table 6.1. Predicted intake of feed by a lactating Merino ewe with a potential intake of 2.13 kg DM/d and the digestibility of its selected diet from a pasture with 0.8 t DM/ha of green herbage, mean digestibility 70%, and 0.4 t DM/ha dead herbage, mean digestibility 45%

	Herbage pool					
	1	**2**	**3**	**4**	**5**	**6**
Dry matter digestibility (%)	80	70	60	50	40	30
Relative ingestibility	1.0	0.83	0.66	0.49	0.32	0.15
Weight of herbage (t DM/ha)	0.24	0.36	0.23	0.16	0.15	0.06
Relative availability[A]	0.39	0.34	0.11	0.05	0.03	0.01
Relative intake	0.39	0.28	0.07	0.02	0.01	0.00
Cumulative relative intake	0.77					
Pasture intake (kg DM)	1.63					
Mean digestibility of diet[B] (%)	73					

[A] After adjusting for the proportion of appetite satisfied by more digestible pools.

[B] Weighted mean for the herbage eaten from all pools.

Increases in intake from feeding nitrogenous supplements will not occur if insufficient sulfur is present in the herbage, and in Chapter 3 it is suggested that 0.07 g S (cattle) or 0.08 g S (sheep) per g N (i.e. per 6.25 g RDP) is necessary. Under some conditions intake has also responded to supplements of sodium, cobalt and selenium (see Chapter 3).

Other factors

Grazing animals exhibit preferences when given ample choice between pasture species, particularly in the very heterogeneous swards characteristic of semi-arid areas (Leigh *et al.* 1968). To a large extent these preferences are based on structural features of the plant that are positively related to its rate of passage through the gut. For naïve animals, these preferences are probably learned by social interaction with animals experienced in eating the same plants (Galef *et al.* 1985), or are conditioned by positive associations between the sensory properties of the plant that the animal uses to recognise the plant (visual, smell, taste, odour and tactile stimuli) and the positive metabolic/neural stimuli generated following its ingestion (Provenza, 1995; Olson *et al.* 1996). Thus, animals preferred *Phalaris aquatica* pasture with a high water-soluble carbohydrate concentration (WSC) in preference to similar pasture with low WSC, even though the low WSC pasture did not differ significantly in DMD or NDF concentration (Ciavarella *et al.* 2000). Aversive conditioning, on the other hand, can cause the animal to avoid certain plants when the post-ingestive metabolic actions are negative, e.g. when the plant contains toxic compounds such as condensed tannins (Provenza *et al.* 1990) oxalic acid (Duncan *et al.* 1998) or phytotoxins (Launchbaugh *et al.* 1993). Such aversions can persist for 4–5 months or longer before they are extinguished (Ralphs 1997). Many preferences tend to disappear as the sward becomes more sparse and they are usually regarded as having little or no independent effect on the total intake of nutrients.

Except during lactation or periods of high environmental temperature, the feed intake by animals grazing improved temperate pastures may be little affected by the availability of drinking water (Lynch *et al.* 1972), but in semi-arid areas the distance that animals have to walk to water may impose an additional limitation on the extent to which they can satisfy their appetite for food in each day's grazing (O'Reagain and McMeniman 2002). This will be particularly severe where the diet has a high salt content or where the land close to water has already been denuded of vegetation (see Chapter 5).

Relating pasture characteristics to model parameters

The independent variables in the functions described in equations 6.8 and 6.10 for the prediction of relative intake define the weight and composition of herbage in each of a number of quality pools. If the functions are being used in a continuous model such as GrassGro (Moore *et al.* 1997) designed to maintain a running budget of pasture and animal parameters over a period of time, then the herbage characteristics will be generated day by day as a consequence of the effects of pasture growth and maturation and grazing. However, a model designed to help tactical decisions on particular pastures and grazing systems at fixed points in time, such as GrazFeed, requires the user to enter an adequate description of current pasture conditions in terms of herbage weight and quality. As it would be difficult for the user to specify the weight of herbage in each of the digestibility pools, the program asks only for the weight and digestibility of two categories, the green and the dead herbage, and the proportion of legume in the pasture.

From this information, the program prepares a suggested profile of the pasture, including its protein content and mean height, any detail of which may then be adjusted by the user.

Weight and height

The two main methods for estimating the weight of herbage dry matter (kg/ha) under extensive grazing conditions are the electronic pasture meter (Jones and Haydock 1970) and the visual estimation technique (Morley *et al.* 1964). McKinney *et al.* (1974) have shown that there is little difference in precision between the two. No doubt there will be continual improvement in the electronic devices available (e.g. Vickery and Nicol 1982) but, at present, all these methods need to be calibrated against direct estimates. If the calibration estimates are made by a cutting procedure that is not compatible with the functions in the model, then adjustments will be necessary. For example, the intake functions in the GrazFeed model are appropriate for herbage weights estimated by running a shearing hand-piece over the surface of the sward and for mean heights measured with a ruler.

On large grazing areas, visual estimation is difficult and the increasing precision of satellite imagery (Henry *et al.* 2002) may lead to a practical alternative in situations where immediate decisions are not required.

Digestibility

Estimates of the mean digestibility of green and dead herbage can be obtained from the digestion *in vitro* of cut samples (Tilley and Terry 1963) or by NIRS (Coleman *et al.* 1999) but quicker assessments are usually needed. The development of individual skills in the visual assessment of weight and digestibility has been extended widely by PROGRAZE courses (Bell and Allan 2000) that, in the southern states of Australia, have trained several thousand graziers. In the estimation of weight, digestibility and protein content, the user's level of precision increases with experience of the pastures and repeated cross-reference to weighed quadrat cuts and analyses of pasture samples.

In the extensive grazing of rangelands, where the feed base is extremely variable but rapid determinations are not as important, NIRS analyses of faecal samples (see above) are likely to provide the best estimates of diet digestibility.

Supplementary feeding

When supplements of grain or processed meals are offered to hand-fed animals eating a basal diet of roughage, the intake of roughage is usually depressed. The depression in the dry matter intake of the roughage divided by the dry weight of supplement eaten is called the substitution rate. This depends on the relative quantities and qualities of the supplement and roughage (Jarrige 1989; Dixon and Stockdale 1999; Dove 2002). For grazing animals, the prediction of the substitution rate is complicated by its interaction with the availability of the pasture. With high quality supplements on high quality abundant pasture, substitution rates are close to 1.0, but on abundant pastures of only 50 per cent digestibility it may be as low as 0.65 (Allden and Jennings 1962). As the weight of pasture falls, and with it the intake of unsupplemented pasture, so does the substitution rate (Langlands 1969; Milne *et al.* 1981; Stockdale 2000).

Because of the obvious complexity in the relationship between supplement and herbage, a set value for substitution rate (as in ARC 1980) is unlikely to be satisfactory. The procedure that

is used in GrazFeed is an integral part of the method for predicting the relative intake of pasture and rests on the simple assumption that the grazing animal will select the supplement before it selects herbage of the same or lower quality (pool d^*). For example, a supplement with a value of 0.9 for relative ingestibility, RQ_s, (equation 6.14) would be selected after 0.09 of the second herbage pool (that, in the absence of legume, has RQ_d of mean 0.83 (see equation 6.7), covering a range from 0.745 to 0.915) but before the remaining 0.91 of the herbage in this pool.

$$RQ_s = \min(1.0, (1 - 1.7(0.8 - DMD))) \tag{6.14}$$

In general, the proportion of herbage in each digestibility class d that is eaten after the supplement is given by equation 6.15.

$$EP_s = \min\left(1.0, 0.5 + \frac{RQ_s - RQ_d}{0.17}\right) \tag{6.15}$$

where 0.1 is the width of a digestibility class.

In the calculation of the term F_s, analogous to the relative availability in a herbage pool (equation 6.9), either the unsatisfied potential intake at this point, UC_{d^*}, or the metabolisability, M/D_s, of the supplement (Grovum 1987) may restrict the intake of the supplement below the amount offered, DMO_s (equation 6.16). The parameters in this function were selected to fit data on substitution rates from Allden (1981), Milne *et al.* (1981) and Stockdale (2000).

$$F_s = \min\left(\frac{DMO_s / I_{\max}}{RQ_s}, UC_{d^*}, \frac{10.5}{M / D_s}\right) \tag{6.16}$$

The effect of the supplement on UC_d is then calculated in equation 6.17:

$$UC_d = \max\left(0, 1 - \sum_{k=1}^{d-1} F_k - F_s\right) \text{ for all d} > d^* \tag{6.17}$$

Table 6.2 shows the predicted effect of offering 0.2 kg per day of a supplement to lactating Merino ewes grazing under the same conditions as those in Table 6.1. In this example, the supplement is equal in relative ingestibility to the first pool of herbage and depresses the relative intake from pasture accordingly.

Table 6.2. Predicted intake of feed by a lactating Merino ewe grazing under the conditions described in Table 6.1, but with the addition of a supplement of DM digestibility 90%, offered at 0.2 kg (air dry)/day

	Suppl.	Herbage pool					
		1	2	3	4	5	6
Dry matter digestibility (%)	90	80	70	60	50	40	30
Relative ingestibility	1.0	1.0	0.83	0.66	0.49	0.32	0.15
Weight of herbage (t DM/ha)		0.24	0.36	0.23	0.16	0.15	0.06
Weight of supplement (kg DM)	0.18						
Relative availability[A]		0.35	0.31	0.10	0.04	0.03	0.01
Relative intake		0.35	0.26	0.07	0.02	0.01	0.00
Cumulative relative intake		0.71					
Pasture intake (kg DM)		1.51					
Total intake (kg DM)		1.69					
Substitution rate[B]	= 0.12/0.18 = 0.67						

[A] After adjusting for the proportion of appetite satisfied by more digestible pools.

[B] Depression in herbage DMI (see Table 6.1) /supplement DMI.

The substitution rates that would be predicted over a wide range of conditions affecting the quality and amount of supplement and pasture are shown in Fig. 6.6. The effects shown in this figure appear to be in general agreement with the experimental results reviewed by Allden (1981), Stockdale (2000) and Dove (2002) but this is certainly one part of the system where more critical work is needed. Recent advances in the use of alkane markers for the estimation of the separate intakes of herbage and supplements by grazing animals (Mayes and Dove 2000) provide promise of a wider range of information in the future.

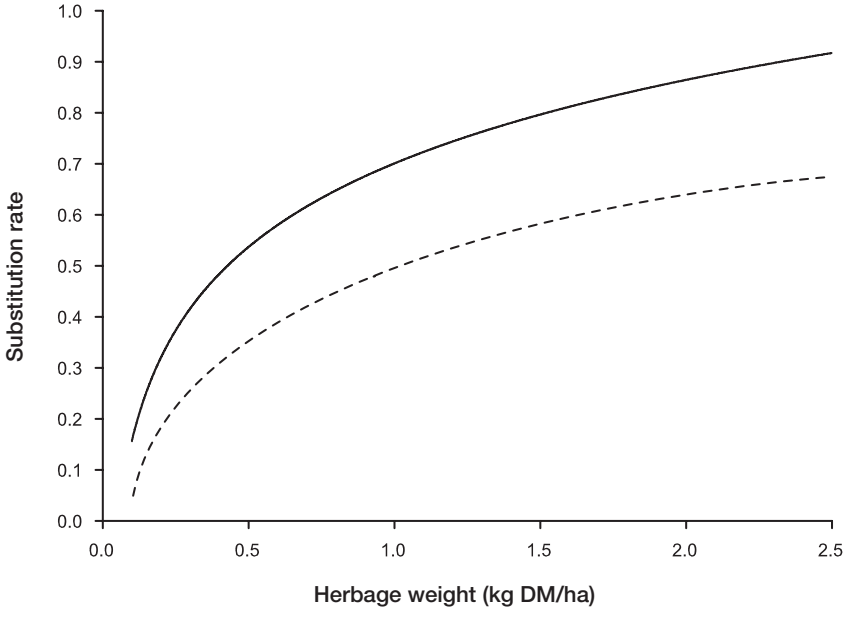


Fig. 6.6. Predicted substitution rate for a sheep offered 200 g of a supplement of 0.8 DMD while grazing a pasture of mean DMD 0.7 (solid line) or 0.5 (dashed line).

If the supplement can rectify deficiencies in the herbage of nutrients such as nitrogen or sulfur, which are restricting the activity of the microbial population in the rumen (see Chapter 3), then the intake of herbage may increase and the substitution rate will be negative (Freer *et al.* 1988). The results of field experiments reviewed by Allden (1981) show wide variability in the responses of grazing animals, but the model being described here allows these supplements to increase herbage intake up to the point where the calculated intake of RDP is no longer deficient.

Prediction of feed intake in practice

It was suggested at the beginning of this chapter that the main use of functions for predicting feed intake would be as components of models of animal productivity. However, for those without the facilities or inclination to use these techniques, some predictions of feed intake by sheep and cattle are shown in Tables 6.3 to 6.6. Tables 6.3 and 6.4, based on equation 6.3, predict the intake of food by growing sheep and cattle respectively, according to their SRW, their actual weight and the quality of the diet. Tables 6.5 (*a* and *b*) and 6.6, based on equations 6.5 and 6.6 respectively, predict the intake of feed by lactating animals on diets of different quality.

These tables are appropriate for hand-fed animals offered a mainly roughage diet or for grazing animals offered abundant pasture.

It is more difficult to generalise in this way about those calculations of relative intake that depend on the characteristics of the sward and on the animal's ability to select from among its components. The values of the constants in these functions will probably depend on the type of pasture and must be obtained from local information. However, an approximation to the effect of pasture conditions on the values predicted in Tables 6.3 to 6.6 can be obtained from Figs 6.4 and 6.5, and for the effect of supplementation from Fig. 6.6.

Validation of the feed intake functions described here has been carried out within the model running in the GrassGro DST (Moore *et al.* 1997) as it difficult to relate, in a satisfactory way, the point estimates from the GrazFeed DST to field measurements made over extended time intervals. Results of these exercises, in Victoria (Australia) and Canada, have been published by Clark *et al.* (2000) and Cohen *et al.* (2003), respectively, and earlier comparisons were presented by Stuth *et al.* (1999).

Table 6.3. Predicted mean intake of feed (kg DM/d) by growing sheep when hand-fed a mainly roughage diet or when grazing abundant pasture[A] (>2 t DM/ha) and selecting a diet of DM digestibility D

SRW (kg)	D	Weight of sheep (kg)							
		20	30	40	50	60	70	80	90
40	0.5	0.49	0.58	0.57					
40	0.6	0.66	0.78	0.77					
40	0.7	0.83	0.99	0.97					
40	0.8	1.00	1.19	1.17					
50	0.5	0.53	0.67	0.74	0.72				
50	0.6	0.72	0.91	0.99	0.96				
50	0.7	0.90	1.14	1.25	1.21				
50	0.8	1.08	1.38	1.50	1.46				
60	0.5	0.56	0.74	0.84	0.89	0.86			
60	0.6	0.75	0.99	1.14	1.19	1.16			
60	0.7	0.95	1.25	1.43	1.50	1.45			
60	0.8	1.14	1.50	1.72	1.81	1.75			
70	0.5	0.58	0.78	0.92	1.01	1.03	1.00		
70	0.6	0.78	1.05	1.24	1.36	1.39	1.35		
70	0.7	0.98	1.32	1.56	1.71	1.75	1.70		
70	0.8	1.18	1.59	1.88	2.06	2.11	2.04		
80	0.5	0.59	0.81	0.98	1.10	1.16	1.18	1.14	
80	0.6	0.80	1.09	1.32	1.48	1.57	1.59	1.54	
80	0.7	1.00	1.38	1.66	1.86	1.97	2.00	1.94	
80	0.8	1.21	1.66	2.00	2.24	2.38	2.41	2.34	
90	0.5	0.60	0.84	1.03	1.17	1.27	1.32	1.33	1.29
90	0.6	0.81	1.13	1.38	1.57	1.71	1.78	1.79	1.73
90	0.7	1.02	1.42	1.74	1.98	2.15	2.23	2.25	2.18
90	0.8	1.23	1.71	2.09	2.39	2.59	2.69	2.71	2.63

[A] These estimates are for a pasture of temperate grasses with 25% legume content; see text for adjustments for other pastures.

Table 6.4. Predicted mean intake of feed (kg DM/d) by growing cattle when hand-fed a mainly roughage diet or when grazing abundant pasture[A] (> 3 t DM/ha) and selecting a diet of DM digestibility D

SRW (kg)	D	Weight of cattle (kg)							
		200	300	400	500	600	700	800	900
400	0.5	3.1	3.6	3.6					
400	0.6	4.1	4.9	4.8					
400	0.7	5.2	6.2	6.1					
400	0.8	6.3	7.4	7.3					
500	0.5	3.3	4.2	4.6	4.5				
500	0.6	4.5	5.7	6.2	6.0				
500	0.7	5.6	7.1	7.8	7.6				
500	0.8	6.8	8.6	9.4	9.1				
600	0.5	3.5	4.6	5.3	5.5	5.4			
600	0.6	4.7	6.2	7.1	7.5	7.2			
600	0.7	5.9	7.8	9.0	9.4	9.1			
600	0.8	7.1	9.4	10.8	11.3	11.0			
700	0.5	3.6	4.9	5.8	6.3	6.5	6.3		
700	0.6	4.9	6.6	7.8	8.5	8.7	8.4		
700	0.7	6.1	8.3	9.8	10.7	11.0	10.6		
700	0.8	7.4	10.0	11.8	12.9	13.2	12.8		
800	0.5	3.7	5.1	6.1	6.9	7.3	7.4	7.2	
800	0.6	5.0	6.8	8.3	9.3	9.8	9.9	9.6	
800	0.7	6.3	8.6	10.4	11.6	12.3	12.5	12.1	
800	0.8	7.6	10.4	12.5	14.0	14.9	15.1	14.6	
900	0.5	3.8	5.2	6.4	7.3	7.9	8.3	8.3	8.1
900	0.6	5.1	7.1	8.7	9.9	10.7	11.1	11.2	10.9
900	0.7	6.4	8.9	10.9	12.4	13.4	14.0	14.1	13.6
900	0.8	7.7	10.7	13.1	14.9	16.2	16.8	16.9	16.4

[A] See footnote to Table 6.3.

Table 6.5a. Predicted mean intake of feed (kg DM/d) by mature lactating Merino[A] ewes with one lamb when hand-fed or when grazing abundant pasture[B] (>2 t DM/ha) and selecting a diet of DM digestibility D

SRW (kg)	D	Time after lambing (d)								
		10	20	30	40	50	60	70	80	90
40	0.5	0.75	0.85	0.87	0.84	0.80	0.75	0.70	0.67	0.64
40	0.6	1.01	1.15	1.17	1.14	1.07	1.01	0.95	0.90	0.86
40	0.7	1.26	1.44	1.48	1.43	1.35	1.27	1.19	1.13	1.09
40	0.8	1.52	1.74	1.78	1.72	1.63	1.53	1.44	1.37	1.31
50	0.5	0.93	1.06	1.09	1.05	1.00	0.94	0.88	0.84	0.80
50	0.6	1.26	1.43	1.47	1.42	1.34	1.26	1.19	1.13	1.08
50	0.7	1.58	1.80	1.84	1.79	1.69	1.58	1.49	1.42	1.36
50	0.8	1.90	2.17	2.22	2.15	2.03	1.91	1.80	1.71	1.64
60	0.5	1.12	1.28	1.31	1.26	1.20	1.12	1.06	1.00	0.96
60	0.6	1.51	1.72	1.76	1.70	1.61	1.51	1.42	1.35	1.30
60	0.7	1.90	2.16	2.21	2.14	2.02	1.90	1.79	1.70	1.63
60	0.8	2.29	2.61	2.67	2.58	2.44	2.29	2.16	2.05	1.96
70	0.5	1.31	1.49	1.52	1.48	1.39	1.31	1.23	1.17	1.12
70	0.6	1.76	2.01	2.05	1.99	1.88	1.76	1.66	1.58	1.51
70	0.7	2.21	2.52	2.58	2.50	2.36	2.22	2.09	1.98	1.90
70	0.8	2.67	3.04	3.11	3.01	2.85	2.67	2.52	2.39	2.29

[A] For adjustments for other breeds, see text.

[B] See footnote to Table 6.3.

Table 6.5b. Predicted mean intake of feed (kg DM/d) by mature lactating Merino ewes[A] with two lambs when hand-fed or when grazing abundant pasture[B] (>2 t DM/ha) and selecting a diet of DM digestibility D

SRW (kg)	D	Time after lambing (d)								
		10	20	30	40	50	60	70	80	90
40	0.5	0.80	0.93	0.96	0.92	0.86	0.80	0.74	0.70	0.66
40	0.6	1.07	1.26	1.29	1.24	1.16	1.08	1.00	0.94	0.89
40	0.7	1.35	1.58	1.62	1.56	1.46	1.35	1.26	1.18	1.12
40	0.8	1.63	1.90	1.95	1.88	1.76	1.63	1.52	1.42	1.35
50	0.5	1.00	1.16	1.20	1.15	1.08	1.00	0.93	0.87	0.83
50	0.6	1.34	1.57	1.61	1.55	1.45	1.34	1.25	1.17	1.11
50	0.7	1.69	1.97	2.03	1.95	1.82	1.69	1.57	1.48	1.40
50	0.8	2.03	2.38	2.44	2.35	2.20	2.04	1.89	1.78	1.69
60	0.5	1.20	1.40	1.44	1.38	1.29	1.20	1.11	1.05	0.99
60	0.6	1.61	1.88	1.93	1.86	1.74	1.61	1.50	1.41	1.34
60	0.7	2.02	2.37	2.43	2.34	2.19	2.03	1.89	1.77	1.68
60	0.8	2.44	2.85	2.93	2.82	2.64	2.45	2.27	2.13	2.02
70	0.5	1.39	1.63	1.67	1.61	1.51	1.40	1.30	1.22	1.16
70	0.6	1.88	2.20	2.26	2.17	2.03	1.88	1.75	1.64	1.56
70	0.7	2.36	2.76	2.84	2.73	2.55	2.37	2.20	2.07	1.96
70	0.8	2.85	3.33	3.42	3.29	3.08	2.85	2.65	2.49	2.36

[A] For adjustments for other breeds, see text.

[B] See footnote to Table 6.3.

Table 6.6. Predicted mean intake of feed (kg DM/d) by mature lactating dairy cows[A] when hand-fed and offered a mainly roughage diet or when grazing abundant pasture[B] (>3 t DM/ha) and selecting a diet of DM digestibility D

SRW (kg)	D	Time after calving (d)								
		30	60	90	120	150	180	210	240	270
400	0.5	5.9	6.5	6.6	6.4	6.2	5.8	5.5	5.2	5.0
400	0.6	8.0	8.8	8.9	8.7	8.3	7.9	7.4	7.0	6.7
400	0.7	10.1	11.1	11.2	10.9	10.4	9.9	9.4	8.9	8.4
400	0.8	12.1	13.3	13.5	13.1	12.6	11.9	11.3	10.7	10.1
500	0.5	7.4	8.2	8.3	8.1	7.7	7.3	6.9	6.5	6.2
500	0.6	10.0	11.0	11.1	10.8	10.4	9.8	9.3	8.8	8.4
500	0.7	12.6	13.8	14.0	13.6	13.0	12.4	11.7	11.1	10.5
500	0.8	15.2	16.7	16.9	16.4	15.7	14.9	14.1	13.3	12.7
600	0.5	8.9	9.8	9.9	9.7	9.2	8.8	8.3	7.8	7.4
600	0.6	12.0	13.2	13.4	13.0	12.4	11.8	11.2	10.6	10.0
600	0.7	15.1	16.6	16.8	16.4	15.7	14.8	14.0	13.3	12.6
600	0.8	18.2	20.0	20.2	19.7	18.9	17.9	16.9	16.0	15.2
700	0.5	10.4	11.4	11.6	11.3	10.8	10.2	9.7	9.2	8.7
700	0.6	14.0	15.4	15.6	15.2	14.5	13.8	13.0	12.3	11.7
700	0.7	17.6	19.4	19.6	19.1	18.3	17.3	16.4	15.5	14.7
700	0.8	21.2	23.4	23.6	23.0	22.0	20.9	19.7	18.7	17.7
800	0.5	11.9	13.1	13.2	12.9	12.3	11.7	11.1	10.5	9.9
800	0.6	16.0	17.6	17.8	17.4	16.6	15.7	14.9	14.1	13.4
800	0.7	20.1	22.2	22.4	21.8	20.9	19.8	18.7	17.7	16.8
800	0.8	24.2	26.7	27.0	26.3	25.2	23.9	22.6	21.3	20.3
900	0.5	13.4	14.7	14.9	14.5	13.9	13.1	12.4	11.8	11.2
900	0.6	18.0	19.8	20.0	19.5	18.7	17.7	16.7	15.8	15.0
900	0.7	22.6	24.9	25.2	24.6	23.5	22.3	21.1	19.9	18.9
900	0.8	27.3	30.0	30.4	29.6	28.3	26.8	25.4	24.0	22.8

[A] These estimates are scaled for cows that have a peak milk yield equal to 0.05*SRW and have been fed to maintain their potential milk yield. See text for adjustments for other conditions.

[B] See footnote to Table 6.3.

Chapter 7

Application

Summary

A number of matters affect the performance of animals fed according to the recommendations in the preceding chapters. Grazing animals, especially, are subject to gastrointestinal parasitism, and severe infections cause reductions in feed intake and the diversion of energy and protein from productive uses to the maintenance of the gut and its immune function. Calcium and P accretion may also be reduced.

The consequences of meal frequency per day for production, and feeds per week in drought are discussed. Performance may be impaired by low intakes of unfamiliar feeds, and there is great variation between animals in their intakes by licking of blocks, which, in consequence, are an unreliable means of mineral supplementation.

Minimum roughage contents required in feedlot diets, and in rations for dairy cows to avoid the low milk-fat syndrome, are discussed. Several feed additives classified as ionophore antibiotics modify fermentation in the rumen and increase propionate production. It is concluded their effect is equivalent to a small increase in the efficiency of use of ME for weight gain; their role in preventing lactic acidosis is compared with the effects of buffers. Ionophores may reduce the protozoal population in the rumen, with the effect of lowering methane production and improving the utilisation of dietary protein.

The principles of nutrition for live export are identical with those for housed or grazing animals, but there are some special problems aboard ship.

The application of recommendations on nutrient requirements for grazing animals can be difficult and laborious, particularly in relation to predicting the quantity and quality of the selected diet. Some computer programs that have been developed to overcome these problems, using the recommendations in this Report, are briefly described.

Introduction

This chapter discusses a number of matters for consideration in the application of the information given in the preceding chapters. It is not the intention to give detailed practical advice on, for example, safe procedures for accustoming animals to diets of wheat grain during drought. Information on this and many other practical problems is given in Bulletins published by all State Departments. The discussion here is directed primarily to circumstances and procedures that modify the nutrition and performance of animals in ways not encompassed in the previous discussions of principles.

Gastro-intestinal parasitism

Predictions of animal performance derived from the information given on requirements are applicable to animals that, in general parlance, would be described as 'normal, healthy'. It is evident that performance will be reduced by any infection. Among these, the only one for mention here is gastro-intestinal parasitism because this is 'normal' to a varying extent, especially in grazing animals.

Interactions between gastro-intestinal parasites and the nutrition of the host have been reviewed by Coop and Sykes (2002). Parasitic infection impairs animal productivity by a reduction in voluntary feed intake, a diminished accretion of Ca and P in the body and less efficient use of absorbed nutrients. Despite earlier claims, there appears to be little effect on the digestibility of protein or energy or on the absorption of protein. The net effects of nematode infection on protein and energy metabolism are that both are diverted from productive uses to the maintenance of the gastro-intestinal tract and its immune function in response to local inflammation. The overall effect is to reduce the supply of DPLS and ME while increasing demand, thereby reducing productive functions.

Both the resistance to infection and the resilience of animals already infected can be markedly improved by supplementation to increase the supply of DPLS. Bown *et al.* (1991) and Datta *et al.* (1999) with young growing animals and Donaldson *et al.* (1998) with breeding ewes have shown that protein supply is more important than energy supply in increasing resistance to infection. Ewes are likely to be most responsive in the last 3 weeks of pregnancy and the first 6–7 weeks of lactation, the period in which they normally exhibit periparturient relaxation of immunity, particularly in relation to abomasal nematodes.

Frequency of feeding

Frequency per day – production

Gibson (1981) concluded that, on average, liveweight gains by cattle were increased by 16.2 ± 4.8% when they were given their ration in four or more meals per day rather than once or twice daily, and that there was a similar effect with sheep. His review indicated that the response occurs predominantly in young animals (cattle less than *c.* 200 kg W, and sheep less than one year old), and is generally greater with diets giving a low daily gain or when there is a high proportion of concentrate feeds (i.e. grain etc.) in the ration. Ruiz and Mowat (1987) found that digestibility and N retention with a high-forage diet given to 250 kg W cattle were higher with four meals per day rather than one, but only when the quantity was restricted and not when *ad libitum*.

With dairy cows, an increased meal frequency can reduce the extent of a depression in milk-fat production caused by low-roughage diets (Sutton 1984; see below). Increased feeding frequency probably reduces fluctuations in the nutritional environment of the rumen microbes, thus promoting a greater net efficiency of fermentation. Animal performance may be increased because of a more uniform supply of nutrients, and the rates of supply will be most variable when feeding frequency is as meals per week rather than per day.

Frequency per week – survival

Rations of wheat grain or other feeds for the survival of animals in drought are commonly provided once or twice weekly, and this procedure confers two major practical advantages.

Compared with daily feeding, there is a substantial reduction in labour requirement though, particularly with once-weekly feeding, the condition of the stock should be monitored frequently. The second advantage is that timid animals in a group are more likely to gain access to feed when the supply for several days is given at one time, whereas dominant animals may consume the whole amount when it is provided daily.

These advantages outweigh nutritional disadvantages. Studies with sheep given ground and pelleted lucerne every 4 d (Graham 1967*b*) or wheat every 7 d (Farrell and Watson 1973; Watson *et al.* 1975) showed that, compared with daily feeding, there was little or no effect on OM digestibility or N balance but there was a higher heat production. The increase, that is a lower net efficiency of ME use (k_m), probably stemmed from energy costs associated with alternation between net anabolism and catabolism of body tissues. However, Franklin and Sutton (1952) reported that wool growth was 5–10% greater with Merino sheep fed weekly compared with daily, and Hill *et al.* (1968) obtained a 55% increase. Hill *et al.* (1968) proposed that the increases could have stemmed from greater MCP synthesis or lesser degradation of dietary CP, giving greater flows of PLS and supplies of amino acids to the animal. It is also possible that catabolism of body tissues between the infrequent meals provided extra amino acids to the wool follicles. Fredericks *et al.* (1986) found that reduced frequency of feeding a supplement (every three days rather than daily) increased wool growth with cereal supplements (oats or triticale) but not with protein supplements (lupins or sunflower meal).

The additional energy expenditure with less-frequent feeding may not be apparent as an additional loss in W by either sheep or cattle (Southcott and McClymont 1960) because a loss in body fat may be offset by a gain in body water (see p. 40).

Feeding behaviour

Studies with sheep by Langlands (1968) demonstrated that there can be variation between animal breeds in the amount of feed (g DM/kg W) grazed from a pasture, and a change with age of animal in the digestibility of the intake. Previous nutritional experience of the animals can have a much larger effect on their intake, and consequently their production. For example, lambs transferred directly from a green pasture to a dry annual pasture ate less and performed worse than lambs with experience of the latter conditions (Arnold 1964). Preferences amongst a choice of pasture plants can also be strongly influenced by experience, as shown by studies (Arnold and Mailer 1977) on diet selection from a pasture by sheep taken from rangelands and by sheep familiar with the type of feed offered.

A sudden change in type of feed can be hazardous; for example, rapid transfer to a high-starch diet such as wheat can result in high mortality from lactic acidosis as described below. Bulletins prepared by State Departments of Agriculture describe procedures that minimise its occurrence when animals have to be fed cereal grain. Apart from this problem, animals may eat little or none of a supplementary feed that they have not previously encountered. They do learn to eat novel feeds by social transmission of behaviour from experienced companion animals, and behaviour learned from adults by young animals before they are weaned persists into later life (Lynch 1986; Mulholland 1986). Such learning is likely to increase the extent to which blocks (e.g. urea-molasses) are licked by animals at pasture. However, Nolan *et al.* (1975) showed very large variation between individual sheep in a flock in their intake of this type of supplement, and subsequent applications of their measurement technique with blocks and other forms of

supplement have consistently given the same result. Animals will often lick salt blocks avidly though they have no need for additional Na, but because of the variation in intake between animals and between days (Rocks *et al.* 1982) the inclusion of other minerals is not an effective way of supplying requirements.

Concentrate:Roughage balance

It is generally desirable to include some long or chopped roughage in formulated rations because of its physiological effects, including increases in saliva secretion and rumen motility. These effects and the fermentation of the roughage promote stability in rumen function and a balance in the absorbed nutrients that is appropriate for normal metabolic processes. With a large intake of starchy feeds, for example, undesirable consequences can include: a low rumen pH particularly because of high lactic acid production; rumen stasis, and damage to its mucosal lining; bloat; the production and absorption of large amounts of propionate that can result in the deposition of soft adipose tissue (Garton *et al.* 1972) and milk with low fat content (see below); and an increased production of histamine.

The development of acute ruminal lactic acidosis on high starch diets has been reviewed by Mackie *et al.* (2002). In animals that have not been gradually adapted to these diets, the rate of production of lactic acid in the rumen by *Streptococcus bovis* exceeds the rate at which it can be used by other bacteria that fail to respond to the diet as rapidly as *S. bovis*. The increasing concentration of lactic acid may lead to clinical acidosis. Acidosis has been implicated in the incidence of cerebrocortical necrosis (CNN) in feedlot cattle during adaptation to a high-concentrate diet, through the increase in thiaminase activity in the rumen (see p. 181).

Lupin grain alone can safely be given to sheep and cattle (Smith and Kenney 1987). Other grains can be fed without a roughage as a survival ration but, in a production diet for stall-fed animals, some roughage is needed to avoid metabolic upsets. Barley or oats are preferred to other cereals because, given rolled but not ground, their husks have a roughage-like nature and effect. The addition of hay or other roughage inevitably reduces the diet M/D, but in numerous experiments reviewed by Preston and Willis (1974) the LWG by cattle was increased by including small amounts of roughage in otherwise all-concentrate diets. Feed intake was always increased, which would have accounted for at least part of the greater gain. Results from these experiments indicated an optimum 20% of diet DM in the form of roughage, which could be materials such as straw or cottonseed hulls and not necessarily hay or silage. Roughage substitutes such as oyster shell and polyethylene have resulted in poorer animal performance. This need for additional roughage does not apply to animals grazing young pasture, where the appearance of scouring merely reflects the limited amount of indigestible dry matter in the faeces.

With lactating cows, there can be a reduction in milk-fat concentration if the proportion of roughage in their diet is low, or if the roughage is ground, reflecting high propionate in the rumen relative to acetate and butyrate. Normally about half of the fat in milk is synthesised from the latter two SCFA, particularly acetate, the remainder being derived from longer-chain fatty acids. With relatively high propionate, milk-fat concentration and production can be sharply reduced, and Annison (1985) concluded that this effect is not simply a consequence of a reduction in the production of acetate precursor; a further cause is that increased propionate production enhances gluconeogenesis, and the increased supply of glucose stimulates insulin secretion that leads to increased utilisation of acetate for the synthesis of adipose tissue and a reduction in blood acetate concentration.

The quantity of roughage that should be included in diets for dairy cows in order to avoid the low-fat syndrome can be assessed with a number of criteria. Sutton (1984) pointed out that the simple approach of providing about half of the DM as hay, silage etc. is flawed because of the variable nature of these materials and of the other feeds used, particularly with respect to the rate and extent of their fermentation in the rumen. An alternative criterion is acid detergent fibre (ADF) concentration, and Sutton (1984) concluded that milk-fat content begins to fall when dietary ADF falls below 200–250 g/kg DM. A further criterion proposed by Mertens (1983) is neutral detergent fibre (NDF), and his studies and those of Briceno *et al.* (1987) indicate an optimum diet content of around 400 g NDF/kg DM. This is close to the level found in young spring pasture (NRC 1996).

With dairy cows grazing pasture, depression in milk-fat concentration is most likely to occur when cereal grains make up more than 50% of the diet. This depression, caused by an increase in gluconeogenesis and reduced lipogenesis in the mammary tissue, can be reversed by supplementing with long-chain fatty acids from oil seeds such as cotton or canola, at rates of up to 50 g oil per kg DM (Walker *et al.* 2004). These authors also review the ways in which the composition of milk fat can be modified through nutrition to meet specific requirements. For all ruminants, the use of dietary oil to increase energy intake should be done with caution; if the contribution from ether extract exceeds 5% of the total energy intake, carbohydrate digestibility in the rumen may be depressed. Treatment of fats to reduce the impact of the free carboxyl groups by, e.g. enriching fats with saturated fatty acids or preparing fats that include Ca salts of long-chain fatty acids, has been shown to reduce the depression of rumen fermentation (Nagaraja *et al.* 1997).

Schingoethe (1996) reviewed the effect of diet on protein concentration in the milk of dairy cows and concluded that it is easier to increase protein yield than concentration. A diet containing large amounts of readily fermentable carbohydrates may increase protein concentration but may also lead to digestive upsets. Supplemental fat that increases milk yield will usually increase milk protein yield but reduce protein concentration.

Feed additives

A number of compounds added to the diet of hand-fed animals, or released continuously from capsules designed to be retained in the rumen (Schlink and Ellis 1982), modify fermentation in the rumen. Their effects on fermentation and animal production have been reviewed by Chalupa (1984) and Nagaraja *et al.* (1997). Non-ionophore antibiotics such as Avoparcin, Bacitracin, Spiramycin and Virginiamycin are being progressively removed from the list of allowable additives because of public health fears (Thomas 2001). The compounds most used are ionophores (e.g. Monensin, Lasalocid, Salinomycin, Narasin, Tetronasin), which all increase propionate production. The consequent reduction in the gaseous end-products of fermentation may reduce the occurrence of bloat. In addition, because propionate production is increased principally through the succinate pathway rather than through lactate, the additives can play an important role in reducing the incidence of lactic acid concentrations that cause acidosis when the diet contains a high proportion of cereal grains.

With increased propionate production, there may be lesser use of absorbed amino acids for gluconeogenesis and potentially more use in protein anabolism. Within the rumen the compounds generally reduce the proportion of dietary protein degraded, but also tend to reduce MCP synthesis, so that there is no significant quantitative effect on CPLS although there is some evidence of an increase with Tetronasin (Graham 1988). The apparent digestibility of OM

does not appear to be altered, but increased propionate production with decreased acetate and butyrate production can have an effect equivalent to an increase in the ME supply. This increase is offset to some extent by a depression in feed intake that is usually observed when the ionophores are given in amounts that effectively modify ruminal fermentation. Lower intakes have been reported for grazing animals (Ellis *et al.* 1988) as well as for those hand fed. The net result in grazing animals, however, is an increase in the rate of gain in W by both cattle and sheep. Increased wool growth has been reported (Graham *et al.* 1984; Aitchison *et al.* 1988) but has not been found in some studies (Ellis and Schlink 1982; Watson and Bogdanovic 1988). None of the ionophore compounds has been registered for use with dairy cows.

Nagaraja *et al.* (1997) reviewed a wide range of experiments that indicated the feeding of ionophores to beef cattle at levels of 50–200 mg/d decreased feed intake by 4%, increased weight gain by 5% and increased efficiency of gain by 9%. The increase in rate of gain by grazing animals given ionophores is variable in extent. Ionophores appear to have least effect in grazing cattle when the rate of gain without the additive is already high, about 1 kg/d. A reason may be that when gain is high the pastures are of a type that yield proportionately high propionate concentrations, so that a further increase with an ionophore is less effective than when the pasture yields less propionate and more acetate.

It is suggested that allowance for the effect of an additive on the performance of growing animals be made simply by assuming a small increase in the value of k_g as predicted from M/D with the appropriate equation (see p. 42).

Studies on the effects of eliminating the protozoal population in the rumen (Bird and Leng 1985) indicate this increases MCP synthesis and the quantity of protein available for intestinal digestion and reduces the proportion of dietary energy lost as methane. In some instances the defaunation has increased liveweight gain by young sheep, and increases in clean wool production have been observed (Bird 1989). In general, it appears that responses by animals to defaunation can occur when the quality of the diet, especially its protein content, is low but are less, or absent, with higher diet quality. At present, however, there is no commercially effective agent for defaunation that can be used without risk to animal health (Hegarty 1999).

The risk of lactic acidosis (see above) can be reduced by the inclusion of buffers, such as sodium bicarbonate (20–40 g/kg DM) or bentonite clay, which act by resisting change in rumen pH and by increasing fractional outflow rate from the rumen (Nagaraja *et al.* 1997) without, however, changing the type of fermentation. Ionophores have a selective antibiotic activity against the major lactic acid-producing organisms *Streptococcus bovis* and *Lactobacillus*, but most of the lactic acid-utilising bacteria are gram negative and are unaffected (Rowe 1985). The use of these pharmaceuticals thus appears to be the appropriate prophylaxis because they act on a basic cause of acidosis rather than, as with buffers, simply diminishing its effects.

Livestock export

The principles of the nutrition of animals aboard ship are identical with those of housed or grazing animals. Practical aspects of their nutrition are discussed in a number of papers introduced by McDonald (1986) and in a report of a workshop (Kellaway 1988). In brief, problems can arise from low intakes because animals are unaccustomed to the type and form (e.g. pellets, dustiness) of the feed, or from inadequate trough space and effects of social behaviour; from lactic acidosis with high-grain diets; from unsatisfactory water supply; and from adverse micro-environmental conditions including high temperature, high humidity, and

ammonia from excreta. Lactic acidosis resulting from a pre-embarkation feedlot preparation may predispose animals to cerebrocortical necrosis (NRC 2006) (see *Vitamin K*). It can be expected that the ME requirements for maintenance would be increased by the animals' responses to their strange environment and other factors, perhaps by 20% or more as observed (Graham 1962) when sheep were, for their first time, isolated in respiration chambers.

Application of recommendations to grazing animals

The recommendations in this Report on nutrient requirements can be applied to the formulation of diets for housed animals in a fairly straightforward manner, particularly with the aid of spreadsheet programs such as ME Required (see p. 52) and CP Required (see p. 101). However, with grazing animals, the amount and quality of the diet selected from the pasture are difficult to measure, even under experimental conditions, and depend on features of the pasture that change from day to day. A scheme for predicting the resulting intake of nutrients is described in Chapter 6 but the manual application of the listed equations to a particular grazing situation would be very laborious. To overcome this problem, a decision support tool (DST), GrazFeed® (Freer *et al.* 1997; Freer *et al.* 2006), has been developed to help the user to assess a specific pasture for a specified class of grazing animals. If the predicted animal production from pasture alone does not meet a desired target, the program will indicate the amount of any specified supplement that would be needed to do so.

The GrazFeed DST (for more information see www.pi.csiro.au/grazplan) implements the functions set out in chapters 1, 2 and 6 of this Report to predict the extent to which the predicted diet will meet the energy and protein requirements of the animals. The accuracy of these predictions depends, of course, on the ability of the user to enter the appropriate descriptions of the particular pasture and animals being tested. A significant hurdle for most users lies in the provision of a quantitative description of the available herbage, a problem that is being overcome by PROGRAZE courses (Bell and Allan 2000), held throughout the southern states of Australia, which have trained several thousand graziers in pasture assessment.

GrazFeed is not concerned with the dynamic nature of the grazing system but is designed to simulate selective grazing and animal production from a particular pasture and grazing system on one day. The output from the DST may indicate, for example, the need to move animals to another paddock, to change the stocking rate or to introduce a particular type and amount of supplementary feed. The DST can be used at regular intervals for continuing re-assessments of nutritional conditions as the pasture matures or is eaten, but it is not designed to test the long-term effects of different grazing policies or changing animal needs. These needs are met by the dynamic DST GrassGro® (Donnelly *et al.* 1997) and AusFarm® (previously known as FarmWi$e, Moore 2001) that combine the animal model in GrazFeed with modules for predicting pasture growth and controlling grazing management. The main purpose of these DST is in testing and optimising grazing strategies and assessing the risks associated with these strategies in relation to climatic variability.

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