Dietary nitrogen – definitions, digestion, excretion and consequences of excess for grazing ruminants

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Abstract

New Zealand pastures often contain a higher concentration of nitrogen (N) than required by ruminants, and this can be exacerbated by application of N fertilisers to boost pasture growth. Excess dietary nitrogen (N) has negative implications for environmental sustainability and animal production, but producers and rural professionals are sometimes unaware of these issues and especially the terminology often used to describe the forms and fate of N. Negative consequences for animal production are mostly defined by the energetic expenditure required for the elimination of N intake in excess to requirements. This is associated with costs for urea synthesis from ammonia absorbed from the rumen and degradation of amino acids that are surplus to animal needs for protein synthesis. Environmental consequences are mainly due to high N concentrations in urine patches. Urine is a major pollutant of waterways and a contributor to greenhouse gas emissions from agriculture.

Keywords: nitrogen, ruminant nutrition, protein metabolism

Introduction

The increase in global demand for food provides New Zealand farmers with an incentive to increase production from their operations. Farmers are using nitrogenous fertiliser (urea) to increase forage yields and profitability, especially in the dairy industry, yet they are required to minimise environmental impacts of farming. Nitrogen (N) utilisation from pastoral farming is under scrutiny from both regional councils (Ledgard *et al.* 2007) and co-operatives (e.g. The Dairying and Clean Streams Accord, Ministry for the Environment 2003) because of potential damage to both the environment (waterways, leachates, groundwater, greenhouse gas) and New Zealand's reputation as a "natural" producer of animal products.

Pastoral farming achieves moderate levels of production per animal (relative to grain based feeding) and a low efficiency of dietary N conversion into saleable product, because excess N cannot be 'stored' in the body and net accrual of N occurs only in body growth, particularly muscles, or the conceptus, fibre or milk. The remainder of the ingested N that is not used for these purposes must be excreted in faeces and urine.

Awareness of environmental issues associated with nitrogen utilisation in pastoral farming has prompted conflicting statements from politicians, environmental advocates, research scientists, farmers and consultants, many with personal agendas. As with many 'hot' topics, different views and terminology are presented, in a range of media channels, so the message can be confusing and conflicting. The purpose of this manuscript is to define some terminology and present an overview of N utilisation by ruminants, highlighting areas we consider critical for improving the efficiency of N utilisation.

Terminology

The animal's need for dietary N has been recognised for over a century and the importance of the 20 amino acids (AA: Table 1) for optimal growth was demonstrated early in the 20th century by Rose and colleagues (Simoni *et al.* 2002). Up to ten AA linked by peptide bonds are termed peptides, and longer chains of AA are termed proteins. All AA contain N, in the amino group, and plant and muscle proteins contain on average 16% N, so multiplying their N concentration by 6.25 (i.e. 100% divided by 16%) gives a value for protein (Table 1). It is less expensive to measure N content by chemical analysis than protein, so multipliers (e.g. 6.25) are widely used to estimate protein concentrations from measurements of N concentration.

One cause of confusion about N metabolism is that all proteins contain N, but not all compounds containing N are proteins (e.g. ammonia, nitrate, nucleic acids, urea). Also, different proteins contain different percentages of N (e.g. milk protein is estimated from N x 6.38). The term "*crude* protein" recognises that much of the N is not contained in *true* protein, but in non-protein nitrogenous compounds. Nevertheless, the terms "protein" and N are widely used, almost interchangeably when describing and discussing ruminant nutrition. From a nutritional point of view, it is important to define these terms more precisely to obtain a better understanding of the issues and challenges regarding N utilisation by ruminants grazing pasture.

Terminology used to describe digestion and utilisation of nitrogenous compounds (Table 1) differs for N in

Table 1 Terminology used in ruminant nutrition to described nitrogen and protein, with emphasis on fresh forage diets.

Terminology	What does it mean?
Crude protein (CP)	Crude protein is equal to N concentration x 6.25. Includes all compounds containing nitrogen (N) as part of their structure. Composed of true protein and non-protein N. Typically 10-30% of the dry matter of temperate forages.
True protein (TP)	Molecules comprising amino acids linked by peptide bonds. Proteins are combinations of 20 different α-amino acids.
Non-protein nitrogen (NPN)	Nitrogen in non-protein forms: primarily nitrates, amino acids, amides, nucleic acids, and ammonia.
Amino acids (AA)	Molecules containing an amine (NH_2) and a carboxyl group (COOH). Rumen microbes can synthesise all 20 amino acids from carbon and nitrogen sources. Ruminant animals can synthesise only 11 of them, while 9 are considered "essential" in the diet.
Forage crude protein fractions	
In the plant	
Fraction 1	TP from forages that is water soluble and rapidly degraded in the rumen. Mainly protein from chloroplasts.
Fraction 2	Mixed proteins, accounting for about 25% of plant TP, slowly degraded.
Rumen and absorbed crude protein	
Soluble (A fraction)	The crude protein that is soluble in water or a buffer. Solubility will depend on plant preparation and the type of buffer used and can be up to 70% of the CP. The A fraction in forages is considered immediately degradable, but degradation is never instantaneous!
Insoluble (B fraction)	The CP that is slowly degraded (3-30% per hour), and accounts for 30-50% of CP.
Undegradable (C fraction)	The CP that is not degraded in the rumen. Mostly associated with cell walls and is 5-15% of CP in forages.
Rumen degradable protein (RDP)	Proportion of the crude protein of a feedstuff that is able to be degraded to peptides, amino acids and ammonia via microbial and plant proteolytic enzymes. The term is best suited to rations based on silages, grains and supplements, rather than fresh forages.
Rumen undegradable protein (RUP)	It includes protein that is not degraded in the rumen due to its structural properties and the fraction of potentially degradable protein that escapes rumen fermentation through rumen outflow. This term is more easily applied to rations based on silages, grains and supplements. The RUP may be hydrolysed in the intestine for AA absorption.
Microbial crude protein (MCP)	Crude protein present in the microbial biomass in the rumen. It comprises true protein (0.7-0.8 of MCP) and microbial non-protein N, mostly nucleic acids (0.2-0.3) of MCP.
Metabolisable protein (MP)	Protein hydrolysed in the intestine and is absorbed for use by the animal metabolism. It comprises dietary, microbial and some endogenous proteins.

plants and animals, and descriptors are often based on analytical characteristics (e.g. solubility), specific types (e.g. microbial CP, nucleic acids) or specific 'pools' (e.g. endogenous protein).

Dietary nitrogen: when does it become too much?

Dietary N can limit ruminant production if supply is insufficient relative to animal requirements. However, in grazing systems with temperate forages, excess N intake relative to requirements can also become a significant additional cost to farming. Nutritional recommendations for N are often expressed as crude protein (CP; N x 6.25; Table 1). For ruminants, where quoted CP requirements represent a composite of the needs of the rumen microbes and the ruminant, the absolute CP requirement in the diet will change depending on the extent of utilisation of N in the rumen *vs.* post-rumen. Thus, diets for high producing cows in the northern hemisphere can be formulated with 15-16% of CP in the DM (e.g. Raggio *et al.* 2004) without compromising productivity because it is possible to manipulate the site of digestion of the CP by using different protein supplements. However, because of the digestion characteristics of CP in temperate forages (see Digestion) the requirements of grazing ruminants can be higher, to compensate for extensive rumen degradation. Thus, dietary CP requirements (% CP in DM) quoted for grazing animals are about 11% for maintenance, 14%

Table 2 Consequences of providing diets with nitrogen in excess of the requirements for production.

What does it mean for the ruminant?

- Nitrogen in excess of requirements has to be disposed of, mostly as urinary nitrogen.
- There is an energetic cost associated with elimination of excess nitrogen.
- There is an energetic cost associated with utilisation of metabolisable protein for productive purposes (milk, meat and fibre).
- High N intakes, or high ammonia absorption, can limit dry matter intake
- High concentration of N can have detrimental effects on animal health, including:
  - Nitrate toxicity
  - Bovine pulmonary oedema-emphysema, associated with high degradation of tryptophan
  - Impaired fertility, notably in overseas cows
- Effects on product flavour through generation of skatole and indole

What does it mean for the environment?

- Nitrogen consumed in excess of the animal's requirement is excreted as urea in the urine, which is concentrated in localised patches on paddocks.
- Transfer of N fertility within a paddock.
- Urine patches result in nitrogen losses to run off, ground water and to nitrous oxides (which account for 17% of New Zealand's greenhouse gases).

for growing cattle and 18% for young or lactating animals. Expressed as N, the values for those animal categories are about 1.8%, 2.2% and 3% of DM, respectively. For animals grazing temperate forages, dietary CP concentrations exceeding 20% (3.2% N) of DM are always surplus to requirements, even for lactating cows.

When dietary CP concentrations meet animal requirements, it is no longer limiting for production, and higher concentrations will not benefit performance. In fact, excessive CP concentrations in the diet can have negative impact on animal production because there are significant metabolic costs for disposal of excess N and also because the energy yield from oxidation of CP to produce high energy phosphate bonds is less than the yield from the volatile fatty acid oxidation (Waghorn *et al.* 2007). Excess N can also have negative impacts on animal and environmental welfare (Table 2). Nevertheless, grasses and legumes selected for temperate systems frequently contain excess CP relative to animal requirements (Brookes & Nicol 2007) and this is made worse by application of nitrogenous fertilisers to boost pasture growth, particularly in spring and autumn.

The role of nitrogen in forages

Forage N content and composition is determined by plant species, maturity, component parts (leaf, stem, inflorescence), and is affected by nutrient supply, climate, fertiliser and management. Nitrogen is present in the forage in a multitude of compounds, including protein, peptides, free amino acids, nucleic acids, nitrates and secondary metabolites (Goswami & Willcox 1969; Mangan 1982).

Most of these compounds serve biochemical functions in the plant and are essential for its growth and reproduction. Major N pools include the enzymes involved in photosynthesis (e.g. ribulose bis-phosphate carboxylase; Rubisco, EC 4.1.1.39) located in the chloroplast membranes, and other enzymes responsible for energy use, growth and turnover of plant components. Smaller depots, but of equal importance include nucleic acids that transfer genetic information during growth and reproduction, and lignified N compounds in forage cell walls. Because protein is contained in constitutive components affecting diverse functions of the plant, it is unlikely that the concentrations can be reduced easily to improve forage quality for ruminants without compromising basic functions such as growth and persistence. However, when excess N is applied as a fertiliser, the pool of the plant N that does not have a functional role increases (Table 3), and appropriate forage management could lower total N concentrations by minimising this pool.

Forage responses to additional N: nutritional and health implications for animals

About 20-30% of the nitrogen content in fresh forages is in the form of non-protein N (NPN) (Mangan 1982), represented by nitrates, free amino acids, peptides and secondary metabolites. Fertilisation with N will increase N concentration in the DM of forage, but the increase will be greater if N is not the first limiting nutrient for plant growth (Nowakowski & Byers 1972; Nowakowski *et al.* 1977). In addition to the increase in total N, nitrogenous fertiliser usually increases the proportion of NPN in the forage (up to 45% of the total N: Table 3) and this can affect nutrition, production and health of the animal. For example, the increase in nitrate (NO_3^-) concentration with N fertilisation may be as much as 10-20 fold and reach 9% of the total N (Wilman & Wright 1978), especially if weather conditions are warm and cloudy. When nitrates exceed 0.23% of the DM, toxicosis

Table 3 Nitrogen (N) constituents in perennial ryegrass receiving 60, 120, 250 and 500 kg N/ha averaged from cuts at vegetative, heading and flowering stages of growth (from Goswami & Willcox 1969).

	N application (kg/ha)			
	60	120	250	500
Total (g/100 g DM)	1.53	1.89	2.69	3.73
Constituents (% of total N)				
Protein	72.0	66.7	65.3	55.2
Peptide	9.1	8.5	6.3	7.2
Free amino acid	10.4	11.1	11.5	15.0
Nitrate and nitrite	2.6	3.2	6.3	9.4
Other organic	2.6	3.2	8.9	10.7

is likely to occur as nitrate is reduced to nitrite (NO_2^-) in the rumen (Bolan & Kemp 2003).

Ruminant nutrition and production may be improved if N application boosts DM production, but in dairy pastures the high concentration of nitrogen in urine patches results in pasture growth that is avoided by cattle. The urine transfers fertility into concentrated patches and results in long pasture and senescence, leading to fungal (*Fusarium*) growth (Keogh 1973), a reduced clover content, and reduced availability of pasture that is readily grazed by cattle. Although not directly related to NPN, *Fusarium* toxins may lower fertility through zearalonone production (Nichol 2007). When feed supply is insufficient, as is typical of intensive dairying (e.g. van Bystveld 2007), animals are forced to eat pasture growing on urine patches, which has an excessive N concentration and brings an increased risk of disease due to fungal toxins and nitrate poisoning.

Digestion

Ruminant digestion comprises both microbial degradation of dietary protein in the rumen followed by hydrolysis and absorption of undegraded forage components and microbial residues in the intestines (Waghorn *et al.* 2007). The hydrolysis of forage protein in the rumen involves both plant and microbial enzymes (Attwood 2005). The microbial activity is the better understood of these two processes: rumen microflora comprise over 100 species with a range of substrate specificities, so CP degradation is usually explained in general terms rather than for specific bacteria or proteins. Terminology for rumen digestion (Table 1; Fig. 1) relates to both the chemical make-up of the nitrogenous compounds (e.g. true protein, NPN – including ammonia arising from protein digestion) and the site of digestion of the CP (e.g. rumen degradable protein (RDP); and rumen undegradable protein (RUP)). With fresh pasture diets the majority of CP is RDP, especially if intakes are low and residence time in the rumen is prolonged.

However, digestion of plant protein is often explained on the basis of its degradation characteristics measured when forage is incubated in porous nylon bags *in situ.* Thus, the dietary CP is described in terms of the soluble and 'immediately degradable' "A" fraction, the insoluble but degradable "B" fraction and the undegradable "C" fraction (typically N in the cell walls). Degradability is measured as a fractional rate (k; h^{-1}) with values ranging from 0.08 to 0.34 for tall fescue and plantain, respectively (Burke 2004). Rates apply only to the "B" fraction which accounts for 40 – 65% of temperate grass, legume, and herb CP (Burke 2004). In perennial ryegrass the "B" fraction averaged 35% of CP with a degradability of 0.12/h (Chaves *et al.* 2006).

The most common assessment of forage quality, other than animal production, is digestibility. Digestibility is the proportional disappearance of nutrients during their transit in the digestive tract; i.e. that proportion (or percentage) of intake that does not appear as faeces. Digestibility is loosely associated with availability for production. However, understanding digestibility is more complicated for CP than for energy because only a relatively small amount of the absorbed N is retained in product, with the rest being excreted in the urine, whereas "excess" energy is stored as body fat. For example, a lamb gaining 200 g liveweight/day from a diet that provides 40 g N/day will retain only 5 g N/day in weight gain (which is mainly fat and water) and wool. Therefore, for a given energy intake, increases in N intake (and digestible N) will result in increased urinary N excretion and not increased animal product (Kebreab *et al.* 2002). Ruminants with high dry matter intakes, such as lactating cows producing 24 kg milk/day from good quality pasture, may consume about 600 g N/day and secrete about 130 g in milk. About 140 g N will be lost to faeces and the remaining 330 g is excreted in the urine. Changes in dietary N intake have relatively little effect on faecal and milk N, and most change is seen in urinary N excretion (Fig. 2), which can exceed 500 g N/day at high N intakes.

It is important to realise that 70% or more of forage CP is degraded in the rumen, and the resulting ammonia is either used by rumen bacteria for their own growth (microbial crude protein, MCP) or absorbed into the blood stream. Once absorbed, the ammonia may be

Figure 1 Diagram of nitrogen transactions in the ruminant. Solid-line boxes represent pools or processes through which dietary nitrogen is channelled. Broken-line (large) boxes represent anatomical sites of utilisation of nitrogen. From dietary nitrogen down to the intestine, the shading of the boxes represents the make-up of nitrogen compounds in each box: gray is for non-protein nitrogen, white is for true protein nitrogen and hatched boxes for a mix of the two.

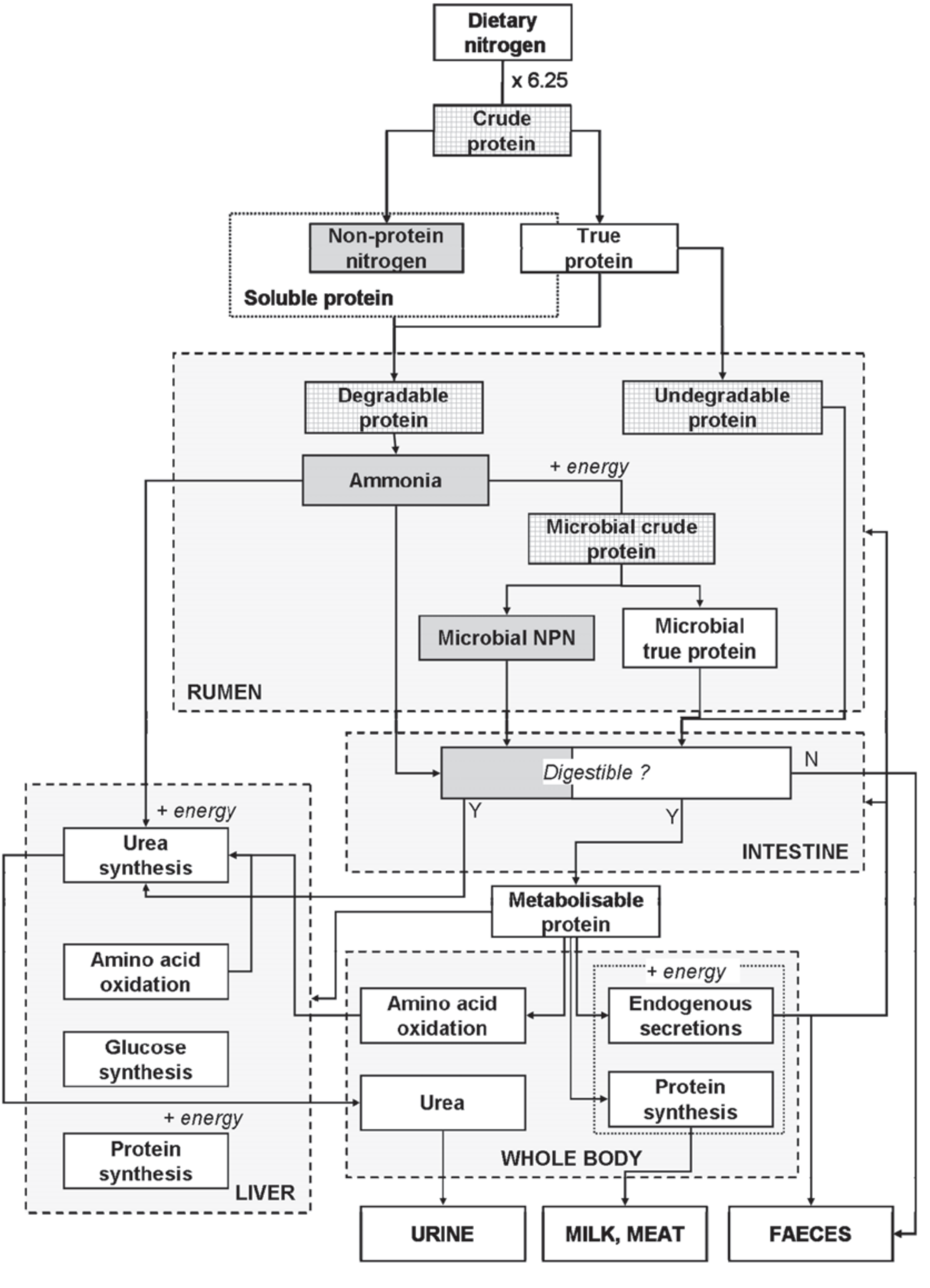
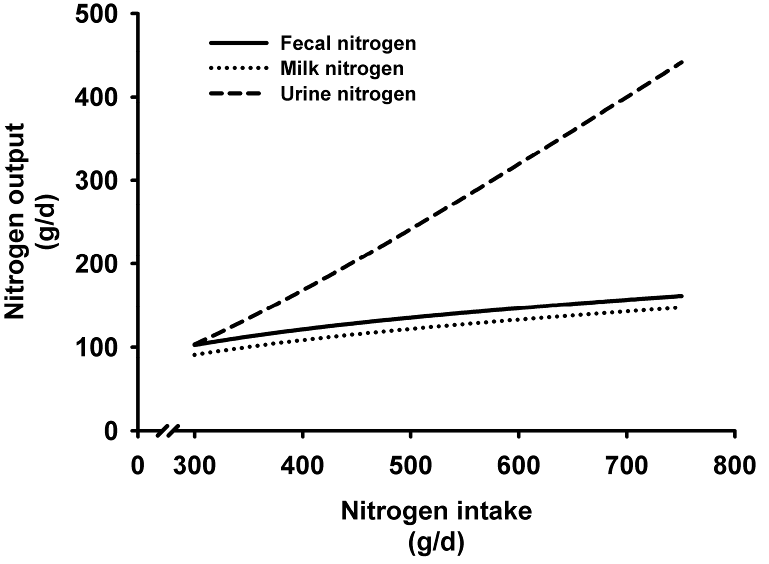


Figure 2 Partition of the dietary nitrogen (N) intake between milk, faeces and urine as derived from Kebreab *et al.* (2002) for cows fed pasture with 85% N rumen degradability and 10.5 MJ of fermentable metabolisable energy per kg DM (equivalent to 12 MJ ME per kg DM).



recycled (Fig. 1) or converted into urea and excreted, mainly in the urine. Some of the AA from MCP and RUP are absorbed from the intestine and are used by the animal for protein synthesis (tissue turnover and production) and those which are surplus to the animal's requirements are degraded, yielding ammonia which is then converted to urea for excretion in the urine.

The efficiency with which N is utilised by the animal can only be improved by increasing animal production (increased N retention, more animal product and/or increased CP content of products) or by reducing the dietary intake of CP. Either way, protein quality is affected by the absorption of essential AA (EAA), rather than digestibility *per se*. For example, the condensed tannin in *Lotus corniculatus* actually reduced N digestion from 78 to 70% but it increased EAA absorption by 60% (Waghorn *et al.* 1987) with commensurate benefits to sheep production (Waghorn 2008).

N metabolism

Nitrogen is utilised by ruminants through a combination of metabolic processes occurring in the rumen microbes and their host, the animal. Although an over-simplification, the rumen microbial populations can use any form of dietary N, but the animal requires AA for its metabolism. The main purpose of the diagram in Figure 1 is to display the fate of dietary nitrogen in the ruminant, and it also highlights the many pools and process through which N is metabolised, and the interactions between nitrogen and energy metabolism. In one such interaction, the rumen microbes are able to use the N for growth provided they have a source of energy (ATP). Rumen microbes require a minimum of 1.2% N in the diet to maintain a functional population (Minson 1991) but recycling of N through saliva enables ruminants to function for several weeks when dietary N is insufficient for the microflora. This is important for ruminant survival in tropical dry seasons. In contrast, excessive ammonia formation from diets with a high RDP content is detrimental both for the microbes and the ruminant (Bach *et al.* 2005). Ammonia is toxic and is removed almost completely from portal circulation during its first pass through the liver (Lapierre *et al.* 2005), with an energy cost of 30 kJ ME/g of nitrogen (Tyrrell *et al.* 1970) illustrating another important interaction between nitrogen and energy metabolism.

Together with the MCP, the digesta outflow from the rumen carries some ammonia, undegraded dietary protein plus endogenous secretions into the small intestine. True protein flowing into the intestine is hydrolysed into small peptides and AA, which are absorbed and made available for the ruminant's metabolic processes (metabolisable protein (MP); Table 1). Proteins in animal products contain 20 AA, nine of which are termed "essential" (histidine, isoleucine, leucine, threonine, lysine, methionine, phenylalanine, tryptophan, valine) because animals cannot synthesise them. The animal's requirement for protein depends on its physiological state and level of production. As little as 50-55 g MP/kg DMI will meet maintenance requirements but 65-85 g MP/kg DMI is needed by growing animals, while up to 110-120 g of MP/kg DMI are required by a lactating cow (National

Research Council 2001; Brookes & Nicol 2007).

Metabolisable protein supply is difficult to measure as it requires surgically modified animals. However, most current feeding recommendation schemes provide ways to estimate absorbable AA in one guise or another based on the chemical composition of the diet and assumed or predicted rates of passage of feed from the rumen (e.g. "metabolisable protein" (National Research Council 2001) "protein digestible in the intestine" (Rulquin *et al.* 1998)).

Not all absorbed AA will be available for productive purposes. Depending on the AA, up to 25% of the amount absorbed (Pacheco *et al.* 2006) may be utilised by the gastrointestinal tract and will "disappear" between absorption and entry to the portal circulation which drains the gastrointestinal tract. Losses are due to the oxidation of amino acids to generate energy for the digestive tract tissues, and also to the secretion of non reabsorbed endogenous protein (e.g. mucous).

In animals fed temperate forages, energy is usually the first limiting nutrient for production (Kolver 2003), so that the supply of AA often exceeds requirements. However there are particular situations in pastoral farming where the supply of AA might be inadequate (e.g. feeding maize silage to dairy cows in summer when pasture has a low CP content). Dietary supply of AA is particularly important because no sizable, readily available body store is available for excess AA, whereas excess metabolisable energy (e.g. in volatile fatty acids) can be stored in fat. Body muscles can be mobilised by the animal during periods of dietary CP inadequacy (Raggio *et al*. 2004) but this process is not sustainable and has obvious adverse effects on the animal. This means that absorbed amino acids which are not utilised for synthesis of product (e.g. due to insufficient dietary energy, or to inadequate animal capacity to synthesise body proteins) are disposed of by oxidation and excretion as urea in the urine.

The disposal of excess AA as urea has the same energetic cost as disposal of ammonia absorbed from the rumen and small intestine (30 kJ ME/g N) and can be as much as the energy provided by 1 kg of DM of forage for lactating cows (350 g N/day x 30 KJ/g = 10.5 MJ), or 4-6% of ME intake. The magnitude of this energy expenditure is now being recognised as part of the energy requirement for production (Fox *et al.* 2004) and will increase ME requirements for animals consuming forages with high nitrogen content.

Consequences of the excess

One consequence of high N diets for ruminants is the energetic cost associated with disposal of the excess N, especially as excess N imposes a metabolic levy on a system already limited by energy supply. Grazing and survey results presented by Ordonez *et al*. (2004) suggest that cows grazing N-fertilised forage will exhibit reduced feed conversion efficiency. In their grazing trial, these authors observed that, in spite of consuming an extra 11 MJ ME/day, cows consuming forage with 25% CP did not produce more milksolids than their counterparts consuming forage with 21% CP. However, there are other metabolic disadvantages for the animal fed excess N (Table 2). These range from potential reduction in dry matter intake associated with high rumen ammonia concentrations (Cosgrove *et al.* 1999), to potentially lethal conditions such as nitrate poisoning (Bolan & Kemp 2003) or pulmonary emphysema when animals are suddenly exposed to a high-N diet (Nichol 2007). In forage-fed animals, the amount and degradability of protein affects the flavour attributes of products (Lane *et al.* 2002). In concentrate fed animals, high plasma urea concentrations have been associated with poor reproductive performance (Ferguson *et al.* 1988), although this effect has not been observed in New Zealand herds (Smith *et al.* 2001).

Environmental consequences of excess dietary N are equally severe and relate mainly to N excretion in the urine. Urinary N is immediately available (unlike faecal N) for leaching or volatilisation. Under wet conditions, the anaerobic environment beneath the urine patch can result in significant N_2O emissions and account for about 60% of New Zealand N_2O emissions (de Klein & Ledgard 2005). Nitrous oxide is a potent greenhouse gas (GHG), about 310 times more effective than carbon dioxide, and accounts for 17% of the New Zealand GHG inventory (Ministry for the Environment 2007). Thus, ruminant urinary N is responsible for about 11% of New Zealand's GHG inventory!

When the risks of ground water pollution, as well as reduced water quality in rivers and lakes (as in the Taupo catchment, Ledgard *et al.* 2007) are added to animal and GHG costs, the excess N intake by most of our ruminants becomes a serious issue. The problem must be addressed, particularly those factors which farmers can control: the use of excess N fertiliser to stimulate growth in pasture species that are 'nitrogen hungry'. We are green, but certainly not clean.

Opportunities for improvement

Farmers choose systems that maximise profitability and sustainability in ways that suit their choice of lifestyle. With the current fertiliser costs (e.g. of urea), high returns (e.g. for meat or milksolids) and absence of environmental taxes (none for urea, leachates or N_2O emissions), choice is often to apply urea to pastures to stimulate pasture growth in spring, autumn and other times. The forages grazed in New Zealand comprise mainly grass, with legumes accounting for only 5-20% of the DM (J.

Caradus, pers. comm), despite their capacity to fix N. These systems are meeting farmer needs, but changes in costs, returns or taxes will influence inputs and management.

Animal agriculture should balance nutrient needs with requirements. This would be best achieved by breeding pasture that has a CP content of about 20% of the DM, maintained over the growing season. This should be a long term breeding objective, but in the immediate future, very high pasture N concentrations can be lessened by applying N fertiliser on the basis of need rather than "because it might help growth". Other benefits of strategic N applications would include reduced risk of nitrate toxicity, while incorporation of legumes would lessen the need for high rates of N application.

Provision of supplements containing low concentrations of N (e.g. maize silage) will dilute high pasture N concentrations in the diet and removing cows from water-logged pastures will lessen N_2O emissions as well as maintain sward quality.

In systems in which supplementary feeding is used, the target should be to reduce the amount of rapidly degradable protein and provide energy for both the microbes and the ruminant to promote the conversion of dietary N into animal product. However, improvements in ruminal N capture will only reduce nitrogen excretion if energy is available to transform absorbed AA into saleable product.

Besides reducing the N intake, the efficiency of N utilisation of a farm can be improved through increases in production achieved per unit of intake. Current work identifying animals with improved feed conversion efficiency from grazed forage (Macdonald & Waghorn 2008) may increase the efficiency of N utilisation for NZ pastoral systems by increasing the proportion of N retained in relation to energy intake.

Cultivars in current use do produce more DM when N fertiliser is applied, and reduced application will lower DM production. The consequences of excess N in New Zealand agriculture are likely to remain until economics forces a change to the way we farm.

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