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A review of efficiency of nitrogen utilisation in lactating dairy cows and its relationship with environmental pollution*

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ABSTRACT

The objective of this paper is to review the literature concerning nitrogen utilisation in lactating dairy cows with an emphasis on their contribution to environmental pollution. Nitrogen, as oxides or ammonia, is one of the green houses gases contributing to air pollution and through leaching to rivers and ground water resources. A quantitative analysis of the contribution of dairy cows to pollution at the farm level is given and the effect of different types of carbohydrate and protein supplementation discussed. The relationship between nitrogen intake and nitrogen balance was investigated using data from 580 dairy cows and 90 treatments published in the literature. Regression analysis described the relationships between nitrogen intake and output in faeces, urine and milk. Inefficient utilisation of nitrogen by dairy cows indicates that about 72% of consumed nitrogen is excreted in faeces and urine. There were positive linear relationships between nitrogen intake and output in faeces, urine and milk up to an intake of 400 g N/d. However, above 400 g N/d, excretion in urine increased exponentially while the rate of increase in nitrogen excretion in faeces and milk declined linearly. To reduce nitrogen pollution, it is recommended to decrease the amount of crude protein in the total diet to approximately 150 g/kg DM which compared with levels of 200 g/crude protein/kg DM consumption can reduce annual nitrogen excretion in faeces by 21% and more importantly in urine by 66%. Management practices with respect to silage making and the choice of supplements need to be considered with the aim of reducing total nitrogen in excreta and if possible shifting nitrogen excretion from urine to faeces.

KEY WORDS: nitrogen pollution, dairy cow, nitrogen balance, model

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INTRODUCTION

Nitrogen utilisation in dairy cows

There are important biological and economical reasons to reduce N losses and improve its utilisation in dairy cattle. One of the major problems of grazed and conserved grasses and legumes is the reduced efficiency of protein utilisation (Beever and Reynolds, 1994). It is accepted that this problem can be overcome with an increased use of protein supplements, but feeding cows with more protein than needed is wasteful, resulting in elevated feed costs, reduced profits (Roffler and Thacker, 1983; Kalscheur et al., 1999) and further reductions in the efficiency of N utilisation (Peyraud et al., 1995). Furthermore, such practices do not always lead to improved lactational performance (Ulyatt, 1997; Santos et al., 1998). Additionally, high intakes of rumen degradable protein are often associated with possible changes in milk composition and this may affect industrial milk quality (e.g. Horne and Muir, 1990; DePeters and Ferguson, 1992; Hermansen et al., 1999).

Excessive N intake, especially as rumen degradable N has been also associated with reduced reproductive performance in dairy cows and low efficiency of body weight gain in steers (e.g. Hibbitt, 1988; Ferguson and Chalupa, 1989; Broderick, 1992; Butler, 1997). Finally, and probably the most important reason to improve N utilisation in dairy cattle is in relation to environmental concern. In the UK and other countries in the EU, dairy farms are regarded as potentially major sources of N pollution (e.g. Korevaar, 1992; Simon et al., 1994; Weissbach and Ernst, 1994; Peel et al., 1997).

Contribution to nitrogen pollution in the environment

The agricultural sector is responsible for about 40% of the anthropogenic nitrous oxide emissions in Europe (Morard, 1999). In the last few decades, the relatively low price of N fertilisers, leading to high rates of N application in agriculture and associated intensive animal production systems have created an important N imbalance in nature, which has significantly contributed to the pollution of the environment (Viets and Hageman, 1971). Dairy farming is responsible for more losses of N in faeces and urine than any other ruminant and non-ruminant systems of production (MAFF Environment, 1994), and is known to contribute to both atmospheric and hydrospheric pollution (Tamminga, 1992).

In the atmosphere, inputs of ammonia have increased by more than 50% since 1950. It is recognised that intensification of animal production systems, with higher number of animals per farm has been one of the major causes of this change (Jarvis, 1994; Asman et al., 1998). Muck and Steenhuis (1982) determined the concentration of urea in urine to be the main factor involved in the volatilisation of ammonia. However, the quantitative relationships between levels and types of dairy cow nutrition, urinary N excretion and ammonia volatilisation in grazing and/or housed dairy cattle has not been fully established (Smits et al., 1995; Asman et al., 1998). There is, however, experimental evidence that appropriate nutritional management of dairy cows may substantially reduce ammonia emissions (Smits et al., 1995). Other workers have also suggested ways of reducing ammonia emissions in agriculture (Korevaar and den Boer, 1990; Tamminga, 1992; Weissbach and Ernst, 1994; Smits et al., 1995; Jarvis et al., 1996; Tamminga and Verstegen, 1996; Asman et al., 1998; Ledgard et al., 1998). Those specifically related to nutrition and N utilisation in dairy cows were (a) reducing N content of animal feeds by adjusting animals requirements to obtain optimal nutrition for each physiological stage of development of the animal, (b) decreased labile rumen N levels by reducing the ruminal degradation of dietary protein and (c) improved energy:protein synchrony in the rumen in order to improve the efficiency of capture of ruminally degraded N through microbial protein synthesis.

With respect to hydrospheric pollution, it was recently estimated that surplus N fertiliser leaching to groundwater as nitrates in grazing systems amounted to approximately 40% of the quantity applied (Ledgard et al., 1998). Nitrate concentration in water is a concern in many areas of Europe. According to the European Union (EU) directive concerning the protection of waters against pollution caused by nitrates from agricultural sources (Council Directive 91/676/EEC), the maximum allowable concentration should be less than 50 mg nitrate/L of drinking water. However, this limit has been exceeded in many UK watercourses over the last few years (Jarvis, 1994).

Objectives

This review focuses on N utilisation in dairy cattle, the effects of protein and energy supplementation and their synchrony on N utilisation and lactational performance, and specifically the contribution of dairy cows fed high quality forage diets to N pollution. Published information on N balance experiments from 580 lactating dairy cows has been collated and the effect of N intake, subsequent N partition to milk, urine, faeces and the efficiency of N utilisation in individual cows and at farm level has been analysed to provide recommendations for reducing N excretions.

NITROGEN UTILISATION IN DAIRY COWS

Effect of protein supplementation on lactational performance

In UK, where grass silage forms the principal forage for dairy cows, it is normal practice to supplement with dairy concentrates containing up to 200 g CP/kg DM (Sutton et al., 1994). There has been much interest in the provision of slowly degradable protein sources to improve amino acid availability in high yielding dairy cows (fish meal or formaldehyde treated soya), by increasing duodenal protein supply as rumen undegradable dietary protein (Beever, 1993). However, lactational responses to rumen undegradable protein supplementation on high quality forage diets have been quite variable (Ulyatt, 1997; Santos et al., 1998).

A large number of studies were compiled in a review on the use of rumen undegradable protein supplements and protein nutrition of lactating dairy cows by Santos et al. (1998). The main conclusion was that increased rumen undegradable protein in dairy cow diets, which often resulted in a decreased supply of rumen degradable protein and a change in the profile of amino acids absorbed, does not consistently improve lactational performance. Alderman and Blake (1995) also observed that increasing the proportion of rumen undegradable protein in the dietary CP fraction for very high yielding cows may result in an inadequate supply of effective rumen degradable protein to the rumen microbes.

Santos et al. (1998) also indicated that fish meal and treated soyabean meal were the sources of rumen undegradable protein that gave the most positive production responses. Broderick (1992) concluded that fish meal gives better responses compared with soyabean meal in early lactation and provides an excellent source of amino acids to the animal. However, fish meal inclusion may affect rumen metabolism (Beever and Gill, 1990) and in some situations has been shown to increase the flow of both microbial and ruminally undegraded dietary protein to the duodenum (Dawson et al., 1988). It is also apparent that not all fish meal sources behave similarly within the rumen, which may be associated with the variable ash and lipids found in some of these products (Beever, 1993).

A more consistent response to increased rumen degradable rather than undegradable protein has been observed on grass and lucerne silage based diets. Reductions in rumen degradable protein supply reduced microbial protein flow from the rumen, which was presumably due to the lack of supply of amino acids and peptides to the rumen microbes (Hoover and Stokes, 1991; Dijkstra et al., 1998). Substitution of part of the rumen degradable protein of grass silage (Sutton et al., 1994, 1996) or lucerne silage (Cadorniga and Sutter, 1993) with a high quality source of rumen degradable protein, tended to improve total DM intake and milk yield with only marginal effects on milk constituent concentration, suggesting that protein, not energy, could be the first limiting nutrient for milk yield on these forages (Dhiman et al., 1993; Dhiman and Satter, 1993; Aston et al., 1994).

Under grazing conditions, the evidence suggests that a production response to rumen undegradable protein will be obtained only if the animal is truly limited in protein and/or amino acids supply (Beever and Siddons, 1986; Ulyatt, 1997; Hongerhold and Muller, 1998). Responses to supplementation of rumen undegradable protein under grazing are not clear. Dhiman et al. (1997) working with high yielding dairy cows supplemented with high maize and roasted soyabeans on a high quality pasture, concluded that the lack of a milk production response to the feeding of a high quality source of rumen undegradable protein was surprising. The authors also indicated that grazed grass was a more effective source of protein than ensiled grass or legume forages, which may contain 50% or more of the CP in non-protein N forms, as discussed by Beever and Siddons (1986) and Beever and Reynolds (1994).

Effect of carbohydrate composition in the supplement on lactational performance

Many experiments have been undertaken to compare the effect of different concentrates with respect to energy or protein content and type on animal performance. A mixture of high quality energy and protein in the concentrate has been shown to increase total dry matter intake and improve lactational performance on grass silage based diets (Sutton et al., 1994; Keady and Murphy, 1998), with similar responses noted for diets based on lucerne silage (Dhiman et al., 1993; Dhiman and Satter, 1993) and grazed temperate pastures (Leaver, 1985). There appears to be two key aspects in the response pattern to concentrate feeds in relatively well balanced diets, namely: (1) the availability of high quality forages with good intake characteristics, especially with respect to silages (Sutton et al., 1996) and (2) the quality of the source of energy and protein in the concentrate. However, Thomas (1984) cited some examples from the literature in which diets supplying similar amounts of ME in the concentrate but differing in carbohydrate composition gave rise to different levels of milk protein production.

The responses to different concentrates at the same level of supplementation are not fully established in dairy cows. Production performance is a major indicator of whether manipulating the site of carbohydrate or protein digestion is a useful technique. Several reviews have compared the effect of starch and/or rumen undegradable protein supplementation on animal performance (Nocek and Tamminga, 1991; Huntington, 1997; Reynolds et al., 1997; Santos et al., 1998). High energy intake appeared to be the main reason for increased production, but in cows at peak lactation fed on a diet containing 180 g CP/kg DM, duodenal starch infusion had no effect on milk protein production or milk yield, which does not support the concept that increased glucose supply from post-ruminal starch digestion will increase milk protein concentration (Reynolds et al., 1996). Taking a number of studies into consideration, Nocek and Tamminga (1991) observed that, although it was possible to shift the site of starch digestion, it was difficult to identify any specific effects of different starch sources, concluding that there was no clear evidence that post-ruminal starch digestion enhances milk yield or changes milk composition which was in agreement with Reynolds et al. (1996). Huntington (1997), stimulated starch digestion and glucose uptake by the small intestine, but concluded that the amount of glucose used by the visceral tissues of ruminants consuming high grain diets is equal to or often greater than the amount of glucose absorbed from the small intestine thus providing no net gains to the animal. It is generally accepted that rumen propionate or glucose directly absorbed by the intestines stimulates an insulin response, which in turn increases the uptake of glucose by non-mammary tissues. In such situations, mammary glucose uptake and hence milk yield are relatively unaffected (Nocek and Tamminga, 1991; Huntington, 1997; Reynolds et al., 1997).

Replacement of cereal starch by various soluble carbohydrate sources, including lactose, whey, molasses and soluble condensed molasses, has been found to prevent or reduce the depression in milk fat caused by low roughage diets. Sutton (1989) concluded that the responses to soluble carbohydrates are often quite variable even with diets containing normal amounts of forage. In cows fed a 70:30 ratio of concentrate to grass silage diet, with the concentrate based on barley or molassed sugar beet feed, total energy output was unaffected. However, the cows fed on the barley based concentrate partitioned more energy to milk with increased energy mobilisation, compared with those on molassed sugar beet feed (Beever et al., 1989). Evaluating different levels of molasses in dairy cows rations, based principally on grass silage, Yan et al. (1997) found that high concentrations of molasses (250 g/kg DM) supplemented with a urea/soyabean meal mix increased milk production, but both fat and protein concentrations decreased when the protein supplements were replaced by unprotected tallow. These studies concluded that lactating dairy cows on diets balanced in protein could be given molasses at an inclusion rate in the total ration of up to 250 g/kg DM without adverse effects on milk production or health. With respect to other non-starch soluble carbohydrates, Belibasakis and Tsirgogianni (1996), replaced dried beet pulp (15% total DMI) and ground maize (8% total DMI) with citrus pulp and found a significant increase in milk fat content and yield but no effect on the production of milk or other milk components, in agreement with Sutton (1989). Santos et al. (1999) however, working with higher yielding dairy cows (over 35 kg milk/d) found an improved performance when high quality rumen undegradable protein and high rumen degradable starch from steam-processed grains were fed with a basal lucerne diet.

The effects of fibre in compound feeds on the performance of dairy cows have been studied under indoor and grazing conditions (Steg et al.,1985; Meijs, 1986; Valk et al., 1990; Aston et al., 1994; Gonda et al., 1996). In general, when the supplement included an increased proportion of fibre rather than non-structural carbohydrates, increased milk fat and decreased milk protein concentrations, with or without changes in total milk production, have been noted.

Synchronising energy-protein in the rumen

The efficient growth of rumen micro-organisms and the consequent optimisation of microbial protein supply to the animal requires the simultaneous availability of substrates, namely energy (carbohydrate) and protein (Dijkstra et al., 1998). Improvements in the efficiency of capture of rumen degradable N by the microbes would reduce the need for expensive rumen undegradable protein sources and also reduce the excretion of urinary N (Sinclair et al., 1993).

Important advances have been made in improving the energy:protein ratio in the rumen and defining animal requirements. These systems are based on the rumen degradable and undegradable fractions of dietary protein (e.g. INRA, 1978, 1988; ARC, 1980, 1984; NRC, 1989). Moreover, calculations for energy and protein requirements now include ruminal rates of degradation of dietary protein (AFRC, 1993) whilst the rate of degradation of different chemical components of the dietary carbohydrate and protein fractions is recognised in some systems (Fox et al., 1992).

Attempts have been made to improve energy and protein utilisation, by consideration of the relative rates of ruminal degradation of these nutritional entities. An index was defined by Sinclair et al. (1993), which described the degree of synchrony between hourly supply of N and organic matter in the rumen, based on *in situ* degradability data. Matching or synchronising energy-protein supply in the diet in order to improve N utilisation in the rumen, has been the aim of several studies with dairy cows (Herrera-Saldana and Huber, 1989; Herrera-Saldana et al., 1990; Kolver et al., 1998; Shabi et al., 1998).

Some positive results have been achieved in terms of rumen microbial N production (Sinclair et al., 1993, 1995) or improved milk production and composition (Herrera-Saldana et al., 1989; Shabi et al., 1998). However, other workers have reported only marginal or often no effects of synchronised diets on milk production and composition (Henderson et al., 1998; Kolver et al., 1998; Witt et al., 1998, 1999). This lack of response may be due to the involvement of other factors, whilst current representations of synchronisation might not have been sufficient to describe the processes of nutrient assimilation in the rumen.

Working under controlled *in vitro* conditions, Newbold and Rust (1992) showed that rumen bacteria were unaffected by synchronisation of nutrient supply. The rumen bacterial population was estimated to be greater at 5 to 8 h post-incubation for synchronised compared with asynchronised treatments, using glucose and urea as substrates, but after 12 h no differences between treatments, leading the authors to conclude that bacterial growth recovered quickly from transient restrictions due to deficits of nitrogen. These results agree with Henning et al. (1993) who concluded that merely improving the degree of synchronisation between rates of energy and N release in the rumen did not give predictable increases in microbial yield.

Ruminal degradation of dietary components depends not only on the chemical nature of each feed and different physical and/or chemical treatments, but also on the competition between rates of digestion and passage (Mertens and Ely, 1979; ARC, 1984; Nocek and Tamminga, 1991; Van Soest et al., 1991), providing an important range of possibilities for each feed. In a report by the Technical Committee on Responses to Nutrients (AFRC, 1999), the authors indicated that it is important to recognise that further modifications to the systems of feed characterisation will need to accommodate new approaches to the prediction of animal response. For fibrous carbohydrates, starch and protein, it seems likely that current chemical descriptions of feeds will prove inadequate for predictive purposes, since estimates of likely rates of degradation of each nutrient fraction when in contact with rumen bacteria are required by all current models.

NITROGEN BALANCE STUDIES AND ANALYSIS

Measurement of nitrogen balance

Nitrogen balance studies have been extensively carried out for many years in order to investigate protein metabolism in human and monogastric animals (Spanghero and Kowalski, 1997). In dairy cattle, these approaches were also used (e.g. Susmel et al., 1995; Gonda et al., 1996), to evaluate feedstuffs (e.g. Keady et al., 1998; Sutton et al., 1998a; Wright et al., 1998), and study ways to reduce N excretion (e.g. Peyraud et al., 1995; Bockmann et al., 1996). Nowadays, N balances are used to define animal requirements whilst considering environmental problems in relation to animal production (Kristensen et al., 1998).

A complete N balance is required to examine the partition of total N intake as N output in faeces, milk, urine and the foetus, and if body weight change occurs, any N retained or mobilised must also be considered (Spanghero and Kowalski, 1997; Kristensen et al., 1998). Bockmann et al. (1996) and Kristensen et al. (1998) found differences in the extent of N excretion with cows in different phases of lactation. There is evidence that the increase in feed intake that occurs in early lactation could affect determinations and may underestimate N intake in cows after calving. Moreover, when cows are pregnant, N retention by the foetus and associated structures becomes quantitatively important in the last two months of lactation or the third trimester of gestation (ARC, 1980). As a result, it is recommended to use dairy cows at similar stages of lactation, with normal intake capacities and when less than 6 months pregnant.

Sources of error in N balance trials were analysed by Spanghero and Kowalski (1997). According to their results, underestimation of faecal N by incomplete collection of material or volatile losses of ammonia during collection or subsequent drying of the samples could be important. The authors evaluated the effects of leaving faeces in the cowshed for different period and recommended collecting faeces at least every 24 h and to determine the N content in wet samples in order to minimise ammonia losses. A second cause of error may be volatile N losses during urine collection and a strong acid (HCl or H_2SO_4) must be used to prevent such losses. From a number of different trials with dairy cows an average N retention of almost 40 g/d was calculated, which converted to total lean tissue, suggests a gain of approximately 1 kg/d (by adopting a coefficient of 6.25, assuming a body protein content of 16% and a ratio of 1:3 protein:water in the body). This estimate appears to be too high, especially for high yielding dairy cows in early lactation. Scurf and dermal losses are other sources of N output, but are difficult to measure and can be considered relatively small when compared to other losses. Spanghero and Kowalski (1997) concluded that underestimation of N losses in balance studies are important, and recommended a number of approaches to improve N metabolism data, specifically to avoid over-estimations of N retention, which have often been reported.

Partition of dietary nitrogen to faeces, urine and milk nitrogen output

Nitrogen excretion in faeces and urine represent a significant proportion of total N intake, and may approach 80% of daily consumption depending on different feed sources (Bruchem et al., 1991). Nitrogen excreted in faeces by dairy cows is reported to be rather constant in proportion to DM intake, about 7.5 g/kg DM ingested according to Peyraud et al. (1995) or 0.6% of the dietary DM intake (Van Soest, 1994). Faeces are composed of undigested feed N, undigested microbial N and endogenous N (Tamminga, 1992), but reduction in faecal N excretion did not appear to be a promising way to achieve any substantial reduction in N loss from the animal (Tamminga, 1992; Van Soest, 1994). This is due to the true digestibility of feed protein in most dairy cow rations being high, whilst digestibility of microbial protein is also high, so suggesting little improvement in digestibility is possible (Tamminga, 1992).

Urinary N excretion on the other hand, appears to be a more promising means by which N output in dairy cattle can be managed. Various routes contribute to urinary N output including ruminal and metabolic losses (Tamminga, 1992). Moreover, increases in dietary protein or N intake generally lead to substantial increases in urinary loss (Van Soest, 1994) with almost all N ingested in excess of animal requirement excreted in urine (Peyraud et al., 1995; Bockmann et al., 1996).

In many countries, high quality forages such as grass silage and lucerne silage are the cheaper components in dairy cow diets and thus represent the main source of N for dairy cattle. However, one of the major problems with these forages is the reduced efficiency of N utilisation. Different solutions have been considered, including supplementation with low rumen-degradable protein, although this is not highly recommended because it could indirectly stimulate N excretion (Peyraud et al., 1995). Increasing readily available carbohydrates in the rumen has also been proposed (Beever and Reynolds, 1994) and several studies comparing the source of carbohydrate as well as protein degradability in the concentrate on N excretion have been undertaken (Castillo, 1999). Valk and Hobbelink (1992) reported several experiments designed to examine the effect on N utilisation of replacing high fertilised herbage by low-protein and high energy feeds, including maize silage and concentrates. Total faecal excretion was estimated by Cr_2O_3 and urinary N excretion as the difference between total N intake and N output in faeces and milk. The authors concluded that partial replacement of high N herbage with feedstuffs containing high energy and low protein reduced urinary N excretion. Moreover, concentrate mixtures based on digestible fibre or starch increased N output in milk, whilst a smaller response was observed with maize silage. According to these studies, fibre-based supplements tended to increase faecal N excretion compared with starch-based concentrates. However, MacGregor et al. (1983) with iso-nitrogenous and high concentrate diets (40:60, forage:concentrate), found no effect on N excretion in faeces or urine when replacing ground maize grain in the concentrate with a high fibre source (hominy feed). Gonda et al. (1996) in two studies also decreased NDF intake whilst increasing starch intake, and found that N balance was unaffected by the treatments, but milk protein concentration was significantly increased on the starch diets. Similar results were obtained by Keady et al. (1998), in which starch content was increased from 50 to 384 g/kg DM but no effects on total N excretion in urine or faeces were observed.

For most cereal grains, at least 90% of the starch is normally digested in the rumen, possible exceptions being maize and sorghum where 30% or so of ingested starch can escape ruminal fermentation, largely to be digested in the small intestine (Ørskov, 1986; Sauvant et al., 1994). However, information comparing different starch sources, with respect to the effect of starch availability in the rumen or the small intestine on N balance in dairy cattle is limited. Petit and Tremblay (1995) working with supplements containing different energy and protein sources and grass silage diets, concluded that high maize when compared with barley diets, could lead to increased fermentation of non-structural carbohydrates in the caecum, which could stimulate microbial protein synthesis and, hence, increase faecal N output at the expense of urinary N excretion. Mason (1969) working with sheep suggested this would decrease urinary nitrogen excretion by increased flux of urea from blood to the large intestine, there to be used by the microbial population in the caecum and ultimately voided as faecal N. This was confirmed by Castillo (1999) who compared iso-nitrogenous diets with barley or maize-based concentrates and found that urinary N excretion was significantly higher in cows fed high degradable starch (barley).

Better defined trends have been observed when evaluating the effect of different protein sources on N excretion. By increasing N availability in the rumen directly as urea (Susmel et al., 1995; Lines and Weiss, 1996) or increasing the N content in grass silage through different fertilisation levels (Peyraud and Astigarraga, 1998), or increasing the ratio of grass to maize silage in the diet (Valk and Hobbelink, 1992; Metcalf et al., 1996; Smits et al., 1997), N excretion as urine was systematically increased with generally negligible effects on faecal and milk N output. In diets with high proportions of rumen degradable protein or an excess of rumen undegradable protein, or both, a substantial proportion of this N will normally be excreted in urine. Castillo (1999) established a significant negative linear relationship between relative (reduced) rumen degradability of protein and urinary N excretion.

An analysis of nitrogen balance data

Data from 91 diets fed to 580 dairy cows in trials carried out in different countries has been collated and used to analyse N utilisation in dairy cows. The data with respect to N output in urine, faeces and milk in relation to N intake is illustrated in Figure 1. Nitrogen intake ranged from approximately 200 to 750 g/d, equivalent to 1.1 to 4.7 kg CP/d. The data included a wide range of feeding situations, from dairy cows supplemented with purified protein-free feed and receiving almost 400 g urea/head/d as the sole source of N (Kreula and Ettala, 1977), to cows overfed with N on high quality pastures or supplemented with high protein concentrate feeds and consuming more than 4 kg CP/d (Valk and Hobbling, 1992; Wright et al., 1998) (Appendix).

Both faecal (N_f) and milk N (N_m) output were linearly related to N intake (N_i) while an exponential increase in urinary N (N_u) output as N intake increased was observed (Figure 1) and these are summarised as follows:

$$N_f = 0.21\,(N_i) + 52.3 \qquad R^2 = 0.48 \qquad (1)$$
$$N_m = 0.17\,(N_i) + 41 \qquad R^2 = 0.42 \qquad (2)$$
$$N_u = 30.4\,(e^{0.0036 N_i}) \qquad R^2 = 0.76 \qquad (3)$$

From this large database, it is evident that urine appears to be the main route of N excretion in dairy cows, especially at N intakes greater than 400 g/d (approximately equivalent to 3 – 3.5 g N/kg$^{.75}$ per day), a level of feeding which suggests that further levels of N supplementation will be used for milk synthesis with very low overall efficiency in average yielding dairy cows. Thus, in cows managed on typical dairy diets a substantial proportion of total N excretion is as urine, which is in agreement with previous reports (Tamminga, 1992; Peyraud et al., 1995; Bockmann et al., 1996). However, studies with high genetic merit dairy cows (over 10000 kg milk/lactation) have suggested that the efficiency of N utilisation and specifically the output of N in faeces and urine (Beever et al., 1998; Cammell, S.B. personal communication, 1999), could differ from the data presented in Figure 1, which is largely representative of dairy cows from average yielding herds.

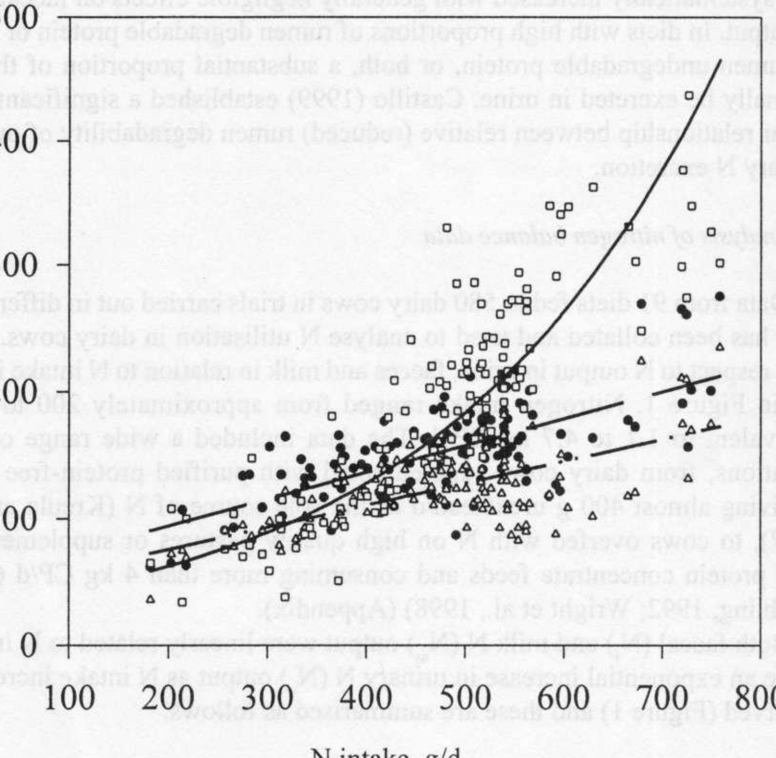

Figure 1. Relationship between total nitrogen intake and output in faeces (●), urine (□) and milk (Δ). The fitted lines were given by equations 1 (—·—), 2 (_._..) and 3 (——)

Coefficients for the estimated efficiencies of conversion of dietary N to faecal (N_{fi}), milk (N_{mi}) and urinary N (N_{ui}) are shown in Figure 2, and the mathematical expressions presented below:

$$N_{fi} = -0.0003\,(N_i) + 0.46 \qquad R^2 = 0.25 \qquad (4)$$
$$N_{ui} = 0.2\,(e^{0.012Ni}) \qquad R^2 = 0.28 \qquad (5)$$
$$N_{mi} = -0.0002\,(N_i) + 0.36 \qquad R^2 = 0.21 \qquad (6)$$

The strength of the relationships was weak possibly due to the nature of the datasets used but the trends are quite clear. As expected, as N intake increased, the proportion of dietary N converted into milk or faecal N declined, and both were represented by linear relationships (Figure 2) such that N was converted to faeces at a rate of 0.40 g/g N intake when cows consumed 200 g/d decreasing to 0.25 g/g N intake when cows ate 750 g/d. Within the same range of N intake, efficiency of N conversion to milk declined from 0.32 to 0.21 g/g, suggesting that an increase in N intake of 300 g/d (from 400-700 g/d) will increase milk N output by only 42 g/d. In contrast, conversion of dietary N to urine N increased exponentially as N intake increased. In part this will be related to the failure of the rumen microbial population to utilise the extra N with the primary route of removing excess ammonia from the rumen being conversion to urea in the liver after absorption, followed by excretion in urine (Van Soest, 1994). As a result, an increase in N intake from 400 to 700 gN/d can be predicted from equation 2 to increase urinary N output by 250 g/d.

Quantitative analysis of nitrogen balance data from dairy farms

Dairy farms are seen as potentially major sources of N emissions (Peel et al., 1997). However, according to Van Der Meer and Van Der Putten (1995), there is little published information about nutrient balance on dairy farms. An analysis of N balances from available information on dairy farms published in different EU countries was compared following the methodology presented by Jarvis et al. (1996). Nitrogen surplus (kg N/ha/year) was estimated as the difference between total N input (as N derived from fertilisers, soil and atmosphere N_2 fixation, and concentrate feeds) and N output (as N in milk, meat, wool, gains and the losses by leaching, denitrification and volatilisation). The efficiency of N secretion in milk has also been considered and expressed in relation to total N input. The results are presented in Table 1, which includes traditional dairy systems with high inputs of nitrogen (HIN) and extensive systems with low inputs (LIN) of nitrogen fertilisers.

The average N input in HIN was 433 kg N/ha/y with almost 90% of this being derived from fertilisers and concentrates. These values are close to those reported by Peel et al. (1997), which indicated total N input in the UK to be between 300-400 kg N/ha. The global average efficiency was 65% and represents an excess (soil retention) of 160 kg N/ha/y (total input – total output). The average efficiency of N retention in milk in high input N dairy systems is low and can

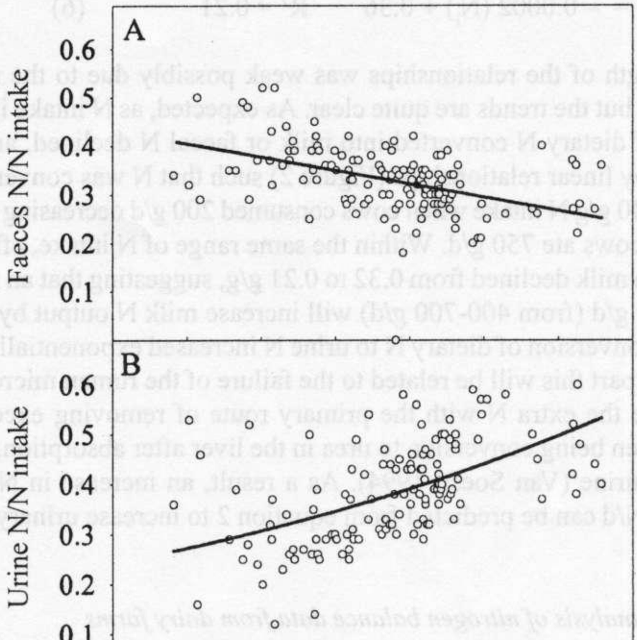

Figure 2. Relationship between total nitrogen intake and output in faeces, urine and milk expressed as a proportion of nitrogen intake. The fitted lines are given by equations 4 to 6 for faecal, urinary and milk N, respectively

fluctuate between 0.12 for a very intensive dairy farms in the Netherlands (Aarts et al., 1992; Korevaar, 1992) to 0.26 under grazing conditions in New Zealand (Ledgard et al., 1998).

The measures to improve N utilisation at the farm level should include: (a) reduced and/or tactical use of N fertilisation, (b) slurry injection, (c) replacement of fertilisers by white clover and (d) inclusion of forage maize in the rotations. A simple evaluation of the impact of these practices is presented in Table 1 (LIN), where an average three-fold reduction in N fertilisation and 40% reduction in concentrate N intake reduced overall N input by more than 50% resulting in a 30% reduction in milk N output but a 60% reduction in N losses by leaching, denitrification and volatilisation. The input of 75 kg N/ha in LIN was similar to the mean of 85 kg N/ha reported for 121 French dairy farms with low N inputs (Simon et al., 1994). Global efficiency was similar between HIN and LIN (0.65 and 0.67, respectively), but the efficiency of N utilisation for milk production increased by

TABLE I

Comparison of N inputs and outputs between high versus low nitrogen fertiliser use in dairy systems, kgN/ha/year

	High nitrogen input		Low nitrogen input	
	average	range	average	range
Input				
fertilizer	296	215 – 413	75	0 – 185
atmosphere	27	2 – 48	24	2 – 40
fixation	30	0 – 117	65	7 – 174
concentrates	73	3 – 173	43	3 – 52
total input	433	337 – 564	207	138 – 269
Output				
milk	75	62 – 92	53	21 – 75
meat, wool, gains, etc.			33	1 – 63
leaching	80	55 – 152	26	14 – 43
denitrification	39	17 – 55	23	5 – 44
volatilisation	45	33 – 65	21	6 – 34
total output	273	223 – 368	136	109 – 176
Total output/N input	0.65	0.44 – 0.80	0.67	0.52 – 0.84
Milk N/total N input §	0.18	0.12 – 0.26	0.27	0.08 – 0.42
Balance	160	89 – 317	71	23 – 108

data from Germon and Couton (1989), Aarts et al. (1992), Weissbach and Ernst (1994), Van der Meer and Van der Putten (1995), Jarvis et al. (1996), Donaghy et al. (1997) and Ledgard et al. (1998).

§ the value in low nitrogen input includes meat, wool, etc.

50% with an important reduction in N retention in the soil of 90 kg/ha/y. Kohn et al. (1997) reported similar data with a 40% reduction in N losses in relation to product output and a 48% increase in total farm N efficiency due to improvements in the nutritional efficiency of the herd.

NITROGEN OUTPUT AND ENVIRONMENTAL IMPACT

The results of this study suggest that substantial changes in the amount and form of N excretion will result when increased levels of N are fed to dairy cows. A predicted intake of 400 g N/d seems to be the critical point in relation to the form in which N is excreted (Castillo et al., 1999). At N intake levels below 400 g/d, faeces is the principal route of N output, but urinary N undoubtedly becomes the major route of N excretion at dietary N intakes above this level. It can be estimated that a N intake of 400 g/d is quite representative of the levels of N consumed by typical dairy cows producing around 20-25 kg of milk/d in an average lactation (AFRC, 1993).

Nitrogen excreted in urine and faeces affects the environment in different ways. With respect to air pollution, Lockyer and Whitehead (1990) reported that volatilisation of ammonia from urinary N was at least 5-6 times higher than from faecal N. In the soil, Pakrou and Dillon (1995) reported that 24% of urine N leached to below a depth of 150 mm in non-irrigated field with the remaining urinary N in the soil converted from urea to ammonium within a day. Because the form in which N is excreted appears to be important in terms of environmental pollution, a further analysis was undertaken to investigate the changes that occur in the pattern of N excretion above and below 400 g N intake/d (Figure 3, equations 7-12). With respect to N intake between approximately 200 to 400 g/d, the relationships between N intake and faecal, urinary and milk N outputs can be best expressed as follows:

$$N_f = 0.38\ (N_i \qquad R^2 = 0.5 \qquad (7)$$
$$N_u = 0.21\ (N_i) + 29.3 \qquad R^2 = 0.16 \qquad (8)$$
$$N_m = 0.23\ (N_i) + 5.8 \qquad R^2 = 0.61 \qquad (9)$$

Kirchgessner et al. (1991) reported values for 153 dairy cows consuming 220 to 430 g N/d of 0.39 and 0.32 (N_i) for faeces and urine, respectively, which were similar to values obtained when the above data were reanalysed excluding this specific dataset (0.37 and 0.29 for faeces and urine, respectively, assuming the origin as the intercept).

With N intakes above 400 g/d, the relationships as presented in Figure 3 were as follows:

$$N_f = 0.23\,(N_i) + 41 \qquad R^2 = 0.33 \qquad (10)$$
$$N_u = 0.67\,(N_i) - 132.7 \qquad R^2 = 0.63 \qquad (11)$$
$$N_m = 0.14\,(N_i) + 56.6 \qquad R^2 = 0.17 \qquad (12)$$

Thus rates of increase for faecal and milk N at N intakes above 400 g/d were much lower than those derived for lower N intakes while urine N was highly affected by the increased level of N intake. This information could be important in defining strategies to re-direct N excretion as faeces or urine and in attempts to rationalise N utilisation in lactating dairy cows using improved feeding models. In areas with N pollution problems, 400 g N/d, which in dietary CP terms represents approximately 150 g CP/kg DM, should be considered as an upper limit of N intake for commercial dairy farms.

To analyse the overall environmental impact of N pollution by dairy cows, it is necessary to determine the actual quantities of N excreted from typical dairy farms. The relationship between total N intake and output as faeces, urine and milk is shown in Figure 4A. For the information used in this study, a significant correlation was obtained between N input and output; with 98% of N intake recovered in faeces, urine and milk. In theory, changes in body weight are not expected in N balance studies because the animals are normally after the peak of lactation or at an early stage of pregnancy.

A significant correlation between N intake and N output was also obtained when only faeces and urine output were considered (Figure 4B), with a substantial inefficiency of N use in lactating dairy cows being observed in a range of feeding situations and milk production levels. On average, about 72% of N intake was excreted in urine and faeces, with an average of 25% recovered in milk N (a single line was fitted to the entire data set shown in Figure 4B) and the equation for the best fit is given by N excreted = 0.72 (N intake; $R^2 = 0.91$). Therefore, from a nutritional point of view, it appears that one of the most important ways to reduce the environmental impact of N from dairy cattle is by reducing total N intake. The efficiency of converting dietary N to milk N obtained in this study is intermediate compared to previous reports in the literature. Kirchgessner et al. (1994) and Bequette et al. (1998) estimated that overall utilisation of dietary N for milk synthesis rarely exceeds 0.30 over a whole lactation. On grass silage and whole crop wheat based diets, efficiency of dietary N conversion to milk N was about 0.29 (Sutton et al., 1998a,b) which increased to 0.32 when a part of the grass silage was replaced with maize silage (Cammell et al., 1999). Sutton et al. (1998a) reported milk conversion rates of up to 0.23 in cows fed urea treated whole crop wheat whilst Wilkerson et al. (1997) with low producing dairy cows, and Bruchem et al. (1991) concluded that the efficiency of dietary N utilisation in European dairy cattle was no higher than 0.20 and still declining.

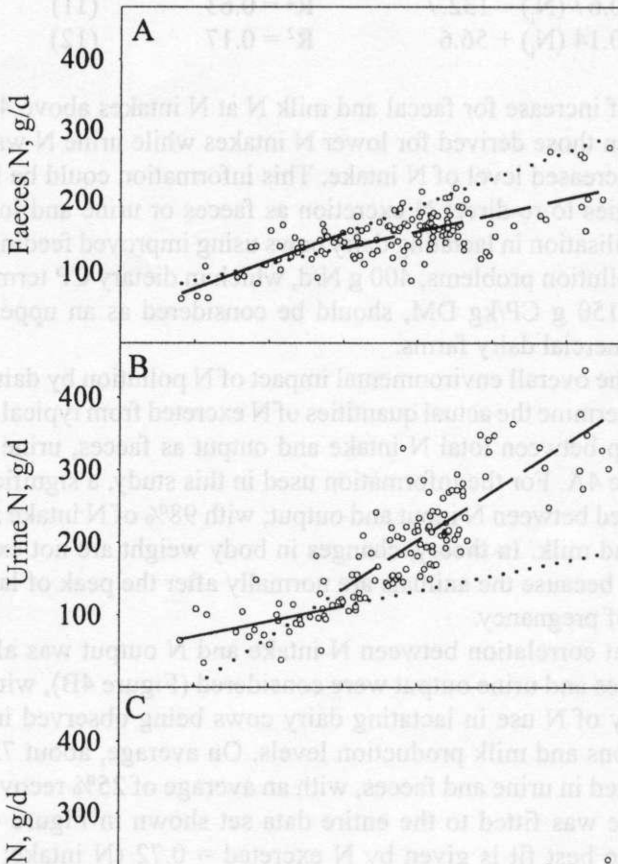

Figure 3. Relationship between N intake and output in (A) faeces, (B) urine and (C) milk in lactating dairy cows at below and above 400 g/d nitrogen intake. Symbols represent data from Appendix. The fitted lines are given by equations (A) 7 (solid lines), 10 (broken line), (B) 8 (solid lines), 11 (broken line) and (C) 9 (solid lines), 12 (broken line) for faeces, urine and milk, respectively. The dotted lines show extrapolations of their respective lines

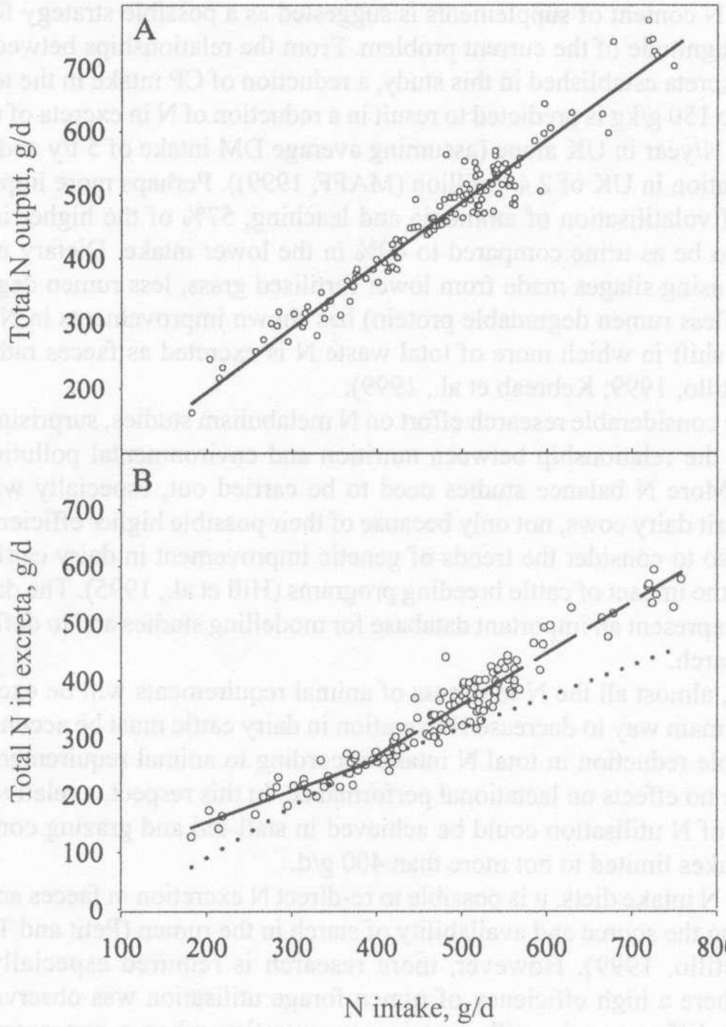

Figure 4. Relationship between N intake (NI) and total nitrogen output as faeces, urine and milk (N_{out})(A); and excreted in faeces and urine alone (N_{Exc}) (B). Symbols were experimental data (Appendix). The derived equations are given by (A) $N_{out} = 0.98$ (NI), ($R^2 = 0.94$), (B) $N_{exc} = 0.55$ (NI) + 43 ($R^2 = 0.78$) (solid line); and $N_{exc} = 0.90$ (NI) – 89 ($R^2 = 0.87$) (broken line). The dotted lines show extrapolations of their respective lines

CONCLUSIONS

In respect to the contribution of dairy cows to environmental pollution, reduction in the N content of supplements is suggested as a possible strategy for reducing the magnitude of the current problem. From the relationships between N intake and excreta established in this study, a reduction of CP intake in the total diet from 200 to 150 g/kg is predicted to result in a reduction of N in excreta of up to 70 million kg N/year in UK alone (assuming average DM intake of 5 t/y and a dairy cow population in UK of 2.44 million (MAFF, 1999)). Perhaps more importantly in terms of volatilisation of ammonia and leaching, 57% of the higher intake is predicted to be as urine compared to 49% in the lower intake. Dietary management (e.g. using silages made from lower fertilised grass, less rumen degradable starch and less rumen degradable protein) has shown improvements in N utilisation and a shift in which more of total waste N is excreted as faeces rather than urine (Castillo, 1999; Kebreab et al., 1999).

Despite considerable research effort on N metabolism studies, surprisingly few studies on the relationship between nutrition and environmental pollution have occurred. More N balance studies need to be carried out, especially with high genetic merit dairy cows, not only because of their possible higher efficiency of N use, but also to consider the trends of genetic improvement in dairy cattle in the world and the impact of cattle breeding programs (Hill et al., 1995). The data from this study represent an important database for modelling studies and to define such future research.

Clearly, almost all the N in excess of animal requirements will be excreted in urine. The main way to decrease N excretion in dairy cattle must be accomplished by a sensible reduction in total N intake according to animal requirements, with minimal or no effects on lactational performance. In this respect, a relatively high efficiency of N utilisation could be achieved in stall-fed and grazing conditions, with N intakes limited to not more than 400 g/d.

On low N intake diets, it is possible to re-direct N excretion in faeces and urine, by changing the source and availability of starch in the rumen (Petit and Trembly, 1995; Castillo, 1999). However, more research is required especially under grazing where a high efficiency of rumen forage utilisation was observed, with significant differences in milk protein concentration when a concentrate with different energy sources were used (Castillo, 1999).

According to the results of this review and those of Santos et al. (1998), more attention must be given to the use of low rumen degradable protein concentrates, especially when considering pollution problems. To quote Thomas (1998) "... there are economic pressures to supplement forage with extra protein and, as the UK has learned to its cost, when the additional protein is of animal origin, the relationship between the N cycle and human affairs takes on a new and sinister dimension".

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STRESZCZENIE

Przegląd literatury na temat wykorzystania azotu przez krowy mleczne i jego związek z zanieczyszczeniem środowiska

Przedstawiony przegląd literatury dotyczy wykorzystania azotu przez krowy mleczne, ze szczególnym uwzględnieniem ich udziału w zanieczyszczeniu powietrza oraz przecieków zanieczyszczeń do rzek i wód gruntowych. Przeprowadzono ilościową analizę udziału krów mlecznych w zanieczyszczaniu środowiska na poziomie gospodarstwa i przedyskutowano wpływ dodatków do diet różnego typu węglowodanów i białka. Zależność między pobraniem azotu i jego bilansem badano wykorzystując opublikowane w literaturze dane uzyskane z 90 doświadczeń przeprowadzonych na 580 krowach. Zastosowanie analizy regresji pozwoliło na opisanie zależności między pobraniem azotu i jego wydalaniem z kałem i moczem oraz w mleku.

Nieefektywne wykorzystanie azotu przez krowy mleczne wskazuje, że około 72% pobranego z paszą azotu jest wydalane z kałem i moczem. Stwierdzono dodatnią liniową zależność między pobraniem azotu i jego wydaleniem w kale, moczu i mleku gdy ilość pobranego azotu nie przekraczała 400 g N/dzień. Jednakże wydalanie azotu w moczu przy pobraniu powyżej 400 g N/dzień wzrastało wykładniczo, podczas gdy tempo wzrostu wydalania azotu w kale i mleku obniżało się liniowo. W celu zmniejszenia zanieczyszczeń azotem zaleca się zmniejszenie ilości białka ogólnego w całej diecie do około 150 g/kg suchej masy, co może obniżyć wydalanie azotu z kałem w ciągu roku o około 21%, a co ważniejsze – z moczem o 66%. W praktyce żywienia krów kiszonkami należy dobierać takie dodatki, które mogą zmniejszyć ilość wydalanego azotu i dążyć, o ile to możliwe, do zmniejszenia stosunku ilości azotu wydalanego w moczu do ilości azotu wydalanego w kale.

APPENDIX

Nitrogen balance in dairy cows, N intake and output in faeces, urine and milk with different diets

Forages	Supplements and fertilizers	Total cows	Nitrogen intake	faeces	milk	urine	References
				g/d			
GS	standard suppl. 200 gCP/kgDM	4	375	124	108	146	Sutton et al., 1998a
2GS:1WCW40	standard suppl. 200 gCP/kgDM		448	169	115	166	
1GS:2WCW20	standard suppl. 200 gCP/kgDM		476	188	115	152	
1GS:2WCW40	standard suppl. 200 gCP/kgDM		479	196	114	183	
Zero grazing	nil	63	266	93	78	104	Keady and Murphy, 1998
GS	nil		218	63	69	100	
GS+sucrose	sucrose		203	65	72	108	
GS+sucrose+fish meal	sucrose+fish meal		284	83	86	148	
GS	50 g starch/kg DM	60	528	159	106	242	Keady et al., 1998
GS	209 g starch/kg DM		521	157	112	243	
GS	384 g starch/kg DM		543	152	111	269	
Zero grazing	0 kg N/ha	4	257	91	91	76	Peyraud et al., 1997
Zero grazing	250 kg N/ha		365	91	93	181	
Grazing	60 kg N/ha	9	423	110	109	204	Astigarraga et al., 1994
Grazing	60 kg N/ha+2 kg soyabean meal		594	132	123	340	
Grazing	300 kg N/ha		503	113	109	281	
Grazing	0 kg N/ha	8	315	102	98	115	Delagarde et al., 1997
Grazing	0 kg N/ha+2 kg soyabean meal		466	119	125	220	
Grazing	250 kg N/ha		585	118	119	348	

APPENDIX – continue

Nitrogen balance in dairy cows, N intake and output in faeces, urine and milk with different diets

Forages	Supplements and fertilizers	Total cows	Nitrogen intake	faeces g/d	milk	urine	References
Grazing	compound feed	27	726	157	132	437	Valk and Hobbelink, 1992
Grazing+CS	nil		501	151	124	223	
Grazing+CS	compound feed		537	140	120	214	
Grazing+CS	compound feed	28	418	177	139	106	Valk and Hobbelink, 1992
Zero grazing+CS	compound feed		372	166	139	51	
Zero grazing	concentrate-high fibre (beet pulp)		376	150	135	98	
Zero grazing	concentrate-high starch (maize)		318	165	122	38	
Zero grazing+CS	compound feed	27	540	161	141	238	Valk and Hobbelink, 1992
Zero grazing	concentrate-high fibre (beet pulp)		491	87	124	285	
Zero grazing	concentrate-high starch (maize)		481	111	123	330	
Grazing	compound feed	35	629	164	102	363	Valk and Hobbelink, 1992
Zero grazing	dry beet pulp		554	162	83	272	
Zero grazing	wet beet pulp		554	149	93	294	
Zero grazing	corn-cob-mix		535	162	93	261	
Zero grazing	maize-ear-ground		547	157	87	272	
Grazing	compound feed	35	604	149	109	347	Valk and Hobbelink, 1992
Zero grazing	dry beet pulp		592	127	88	291	
Zero grazing	wet beet pulp		562	139	95	281	
Zero grazing	corn-cob-mix		562	130	90	264	
Zero grazing	maize-ear-ground		562	130	95	271	
GS	suppl. (213 gCP/kgDM)	6	526	178	124	169	Metcalf et al., 1996
GS+CS	suppl. (163 gCP/kgDM)		424	157	122	122	

APPENDIX – continue

Nitrogen balance in dairy cows, N intake and output in faeces, urine and milk with different diets

Forages	Supplements and fertilizers	Total cows	Nitrogen intake	faeces g/d	milk	urine	References
Fescue hay	compound feed (+urea 0/kg)	8	214	107	75	34	Susmel et al., 1995
Fescue hay	compound feed (+urea 20 g/kg)		295	109	91	72	
Grazing, CS, GS	compound feed + LF	19	473	142	161	149	Bockmann et al., 1997
Grazing, CS, GS	compound feed + HF	19	501	141	142	181	
Lucerne hay	suppl. + 1.2% urea	15	486	164	145	163	Lines and Wiess, 1996
Lucerne hay	suppl. + 19% soyabean meal		415	118	143	124	
Lucerne hay	suppl. + hay ammoniated		418	147	129	111	
Lucerne hay	suppl. + animal protein		431	160	146	123	
Silage 40%	suppl. 60% high TNSC	12	468	159	156	143	MacGregor et al., 1983
Silage 40%	suppl. 60% low TNSC		444	144	158	147	
Feed restriction 20%	low DUP	6	275	134	95	70	Wright et al., 1998
Feed restriction 20%	medium DUP		492	173	112	185	
Feed restriction 20%	high DUP		665	178	118	331	
Feed restriction 10%	low DUP		302	157	98	59	
Feed restriction 10%	medium DUP		468	186	111	154	
Feed restriction 10%	high DUP		672	173	121	303	
High forage	low concentr. low fat	4	505	183	137	197	Gonda et al., 1996
Low forage	high concentr. low fat		521	182	156	195	
High forage	low concentr. high fat		474	157	117	208	
Low forage	high concentr. high fat		497	152	139	214	

APPENDIX – continue

Nitrogen balance in dairy cows, N intake and output in faeces, urine and milk with different diets

Forages	Supplements and fertilizers	Total cows	Nitrogen intake	faeces	milk	urine	References
			g/d				
Purified CP-free diets	suppl. urea 370 g/d	10	182	62	36	65	Kreula and Ettala, 1977
GS direct early cut	compound feed+HF	6	445	129	122	241	Kebreab et al., 1999
GS direct early cut	compound feed+MF		540	168	146	214	
GS early cut wilted	compound feed+MF		517	179	139	222	
GS early cut wilted	compound feed+HF		557	165	143	217	
GS direct late cut	compound feed+HF		481	129	126	205	
GS wilted late cut	compound feed+HF		486	136	139	221	
GS wilted	HF + suppl. starch + fibre	6	395	143	122	118	Kebreab et al., 1999
GS wilted	MF + suppl. starch + fibre		409	157	131	105	
GS wilted	LF + suppl. starch + fibre		345	133	115	87	
GS wilted	suppl. starch		378	149	129	94	
GS wilted	suppl. fibre		387	140	116	113	
GS+NH_4 tetraformate	mix suppl.	6	467	157	135	153	Kebreab et al., 1999
GS+bacterial inoculant	mix suppl.		459	163	130	144	
GS+organic acids	mix suppl.		482	167	146	145	
GS	suppl. barley grain		476	161	138	154	
GS	suppl. maize grain		462	164	137	140	
TMR	GS + compound feed	6	399	154	122	121	ADAS Bridgets, UK (unpublished)
Grazing	compound feed		518	176	124	170	

APPENDIX – continue

Nitrogen balance in dairy cows, N intake and output in faeces, urine and milk with different diets

Forages	Supplements and fertilizers	Total cows	Nitrogen intake	faeces g/d	milk	urine	References
GS	nil	4	502	177	93	216	Petit and Tremblay, 1995
GS	maize grain		555	191	112	211	
GS	barley and oat grains		543	179	107	216	
GS	sugar beet pulp+soyabean		559	190	109	187	
GS	sugar beet pulp+fish meal		565	201	112	234	
Grass pellets+hay	compound feed	11	374	156	105	108	Kirchgessner et al., 1991
Grass pellets+hay	compound feed	12	334	147	86	114	
Grass pellets+hay	compound feed	19	314	135	74	92	
CS+hay	compound feed	34	343	140	100	93	
CS+hay	compound feed	20	338	126	93	88	
CS+hay	compound feed	32	329	120	84	77	
CS+hay	compound feed	25	312	116	79	100	
(Total treatments = 91;	total cows = 580)		N intake	N faeces	N milk	N urine	
Average, g/d			454	145	115	181	
Min, g/d			182	62	36	34	
Max, g/d			726	201	161	437	
N intake/N output				0.32	0.25	0.40	

GS = grass silage, LF = low nitrogen fertilisation, WCW = whole crop wheat, MF = medium nitrogen fertilisation, CS = Corn (maize) silage, HF = high nitrogen fertilisation, TMR = total mixed rations, TNSC = total non-structural carbohydrates and DUP=digestible undegraded protein