

# Focus on Efficiency: Coordinating Dietary Starch and Protein Utilization in the Rumen

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## ■ Take Home Messages

- ▶ Fermentative processes in the rumen provide volatile fatty acids, which are a major source of energy, and microbial crude protein, which is a major source of amino acids, for use in milk production by the dairy cow
- ▶ The efficiency of nitrogen utilization in the rumen is usually low, leading to substantial losses of dietary nitrogen as urinary urea
- ▶ The amount of ruminal energy (primarily from carbohydrate fermentation) limits microbial crude protein synthesis in the rumen
- ▶ Matching ruminal protein and carbohydrate fermentation in the rumen can increase microbial crude protein synthesis, but responses have been inconsistent

## ■ Introduction

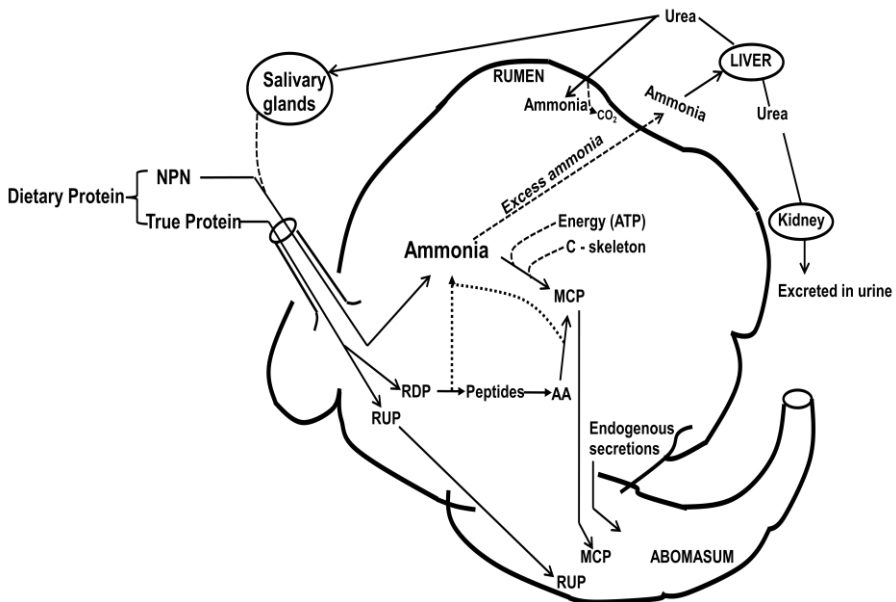
The rumen, which is sometimes described as a fermentation vat, is home to 3 major groups of microorganisms: bacteria, protozoa and fungi. The relationship between the dairy cow (host animal) and the ruminal microorganisms is synergistic in nature. The host animal provides a constant supply of feed in an environment that is conducive for the proliferation of the microorganisms. In return, the microorganisms ferment the feed, resulting in the production of volatile fatty acids (VFA) that are utilized by the dairy cow as an energy source and, in addition, the microorganisms become a major source of amino acids for the dairy cow when they are washed out of the rumen and subsequently digested in the small intestine. This source of amino acids for the dairy cow is referred to as microbial crude protein (MCP). Microbial crude protein synthesis in the rumen uses primarily energy and nitrogen (N) as growth factors, and their synchronous availability is usually associated with increased MCP synthesis. Although the presence of ruminal microorganisms gives dairy cows the ability to convert poor-quality, high fiber

feeds into nutrients that can be used for milk production, it can be a major cause of inefficient N utilization as some of the dietary N is wasted. This paper focuses on how dietary carbohydrate (mainly starch) and protein utilization in the rumen can be synchronized in order to maximize MCP synthesis, thereby improving the efficiency of N utilization.

## ■ How the Rumen Works

Of the 3 groups of rumen microorganisms, bacteria and protozoa are the most important as they perform most of the fermentative functions (NRC, 2001). These microorganisms ferment dietary organic matter (OM; primarily sugars, starch, fermentable fiber, protein) to VFA, mainly acetate, propionate and butyrate. These VFA are absorbed across the rumen wall into the bloodstream and they provide up to 70% of the dairy cow's energy requirements (NRC, 2001). The proportions in which these VFA are produced in the rumen largely depend on the nature of the diet fed, and this will also have a major influence on the composition (i.e., fat and protein content) of milk (NRC, 2001). In fermenting dietary OM, ruminal microorganisms obtain energy (ATP) and other nutrients that are needed for their growth; however, the major "driver" for the growth of ruminal microorganisms is energy.

According to NRC (2001), dietary protein can be classified into 2 broad categories: 1) ruminally-degradable protein (RDP), which is dietary protein that is degraded by ruminal microorganisms and provides most of the N that is required for MCP synthesis; and 2) ruminally-undegradable protein (RUP), which is dietary protein that escapes degradation in the rumen and is digested by the host animal's enzymes in the small intestine. The RUP fraction is commonly referred to as bypass protein. In addition to true protein, RDP also includes non-protein nitrogen (NPN), which is composed of N that is present in ammonia, amino acids, and small peptides (Bach et al., 2005). The relative proportions of RDP and RUP in feedstuffs depends on the nature of the feedstuff (its protein structure, particle size etc.) and environmental conditions in the rumen (e.g., ruminal pH, predominant microbial species etc.). The breakdown of RDP in the rumen produces mostly ammonia-N, which is the major source of N for MCP synthesis; however, amino acids and small peptides arising from RDP degradation can also be used as N sources for MCP synthesis (Bach et al., 2005). The sequestration of N for MCP synthesis depends primarily on the amount of energy that is available mainly from carbohydrate (starch) fermentation (NRC, 2001). If energy is limiting, then N can be wasted as discussed later. Figure 1 illustrates the major N transactions in the rumen.



**Figure 1. Overview of nitrogen metabolism in the rumen. NPN = non-protein nitrogen; RDP = ruminally-degradable protein; RUP = ruminally-undegradable protein; AA = amino acids; and MCP = microbial crude protein.**

## ■ Why is Microbial Crude Protein Important to the Dairy Cow?

Ruminal microorganisms are continually being washed out of the rumen to the abomasum and small intestine where they die and are then digested to individual amino acids by the dairy cow's enzymes. Lactating dairy cows absorb a wide array of individual amino acids, which are the "building blocks" of proteins, and these amino acids are utilized for maintenance, reproduction, and milk production. Besides MCP, amino acids are also derived from the digestion of RUP in the small intestine. When these 2 sources of amino acids are digested and absorbed in the small intestine, they are collectively referred to as metabolizable protein (MP). There are 3 major reasons why it is important to maximize MCP synthesis in the rumen. Firstly, MCP is by far the most important component of MP reaching the small intestine in dairy cows, contributing more than 60% of MP (NRC, 2001). Secondly, on a qualitative basis, MCP has an amino acid profile that closely matches the amino acid requirements for milk protein synthesis (NRC, 2001), and this amino acid profile is superior to that of most common feed ingredients that are fed to dairy cows (Schwab, 2001; see Table 1). For lactating cows, methionine is

usually the first limiting AA when diets based on oilseed- or animal-derived proteins are fed, whereas lysine is the most limiting when diets based on cereal grains (corn, barley etc.) or cereal grain-derived feeds (e.g., distillers grains with solubles) are fed (NRC, 2001). For most feed ingredients, except fish meal which is not commonly fed to dairy cows, contents of lysine and methionine are considerably less than in milk or MCP (Table 1). Thirdly, when MCP synthesis in the rumen is maximized, then fermentative processes in the rumen are optimized and feed intake can usually be maximized thereby maximizing nutrient supply for milk production.

**Table 1. Lysine, methionine, and histidine contents (expressed as a percentage of crude protein) of milk, rumen bacteria, and typical feed ingredients that are commonly used in dairy rations**

	Lysine	Methionine	Histidine
Milk	7.6	2.7	2.7
Rumen bacteria	7.9	2.6	2.0
Alfalfa silage	4.4	1.4	1.7
Corn silage	2.5	1.5	1.8
Barley	3.6	1.7	2.3
Corn	2.8	2.1	3.1
Oats	4.2	2.9	2.4
Wheat	2.8	1.6	2.4
Canola meal	5.6	1.9	2.8
Corn dried distillers	2.2	1.8	2.5
Corn gluten meal	1.7	2.4	2.1
Cottonseed meal	4.1	1.6	2.8
Soybean meal	6.3	1.4	2.8
Sunflower meal	3.6	2.3	2.6
Fish meal	7.7	2.8	2.8

Source: Schwab (2001).

## ■ Rumen Fermentation Usually Results in Wastage of Nitrogen

Although the presence of ruminal microorganisms confers the ability for dairy cows to convert cellulosic feeds into nutrients that fulfill productive needs and is the only mechanism for NPN use, it is also a major cause of inefficient use of dietary N. Milk N efficiency (MNE) is a commonly-used index for assessing the efficiency of conversion of feed N into milk N in dairy cows, and it is calculated as the quantity of N secreted in milk expressed as a proportion of

feed N intake. Under field conditions, MNE values in dairy cows range from 20 to 35% (Chase et al., 2009). What this means is that most of the feed N (65 to 80%) that a dairy cow consumes is excreted in feces and urine, thereby potentially causing environmental damage. Because protein is one of the most expensive components of dairy cow rations, such N losses are also economically costly. Because of concerns relating to inefficient N utilization, considerable research efforts have been directed towards improving N usage in the rumen. The fermentative processes in the rumen are a major contributor to inefficient N utilization. If energy availability in the rumen is limiting, the ability of microorganisms to sequester ammonia-N for MCP synthesis is diminished. In that case, excess ammonia-N is absorbed across the rumen wall into the bloodstream and transported to the liver where it is used for urea synthesis. Most of the urea is then excreted in the urine, thereby representing an irreversible loss of N to the dairy cow (NRC, 2001).

## ■ **Nutrient Synchrony and Effects on Microbial Protein Synthesis in the Rumen**

As already mentioned, MCP synthesis in the rumen is largely “driven” by the availability of energy (mainly from carbohydrate fermentation) and N. Therefore, synchronizing the rates of carbohydrate and protein (RDP) degradation in the rumen, a concept commonly referred to as nutrient synchrony, as a strategy to optimize MCP synthesis has been a focus of considerable research attention. With nutrient synchrony, the rate of carbohydrate fermentation is closely matched with that of protein degradation, and this should result in a coupling of energy (ATP) production with ammonia-N release. When nutrient synchrony occurs, the capture of ammonia-N for MCP synthesis is increased, thus improving MP supply to the dairy cow and, thereby, improving milk and milk protein production. Conversely, when uncoupled fermentation occurs i.e., when there is asynchronous carbohydrate and protein degradation in the rumen, large amounts of ammonia-N are absorbed across the rumen wall into the blood or energy use for MCP synthesis will decrease (Bach et al., 2005), leading to a decrease in MP supply (Nocek and Russell, 1988).

Typically, carbohydrates make up 70 to 80% of the dairy cow’s diet (Nocek and Russell, 1988). In western Canada and the USA, dairy cow diets usually contain barley or corn as the main carbohydrate source. These cereal grains differ in their starch contents with corn containing (DM basis) 72% starch and barley 57 to 58% (see review by Huntington, 1997). Differences also exist between these cereal grains in their rates and extents of ruminal starch degradation, with 55 to 70% of corn starch and 80 to 90% of barley being fermented in the rumen (Huntington, 1997). Because barley and corn differ in their starch contents, and in their rates and extents of ruminal starch digestion, their ability to support ruminal MCP synthesis is different. Also,

commonly-used protein sources like canola meal and soybean meal differ in their physical and chemical characteristics, meaning that they differ in their RDP contents and the diurnal patterns of ammonia-N release in the rumen (NRC, 2001). Therefore, one approach to achieve nutrient synchrony that has received considerable attention is the manipulation of dietary carbohydrate and protein sources (NRC, 2001; Cabrita et al., 2006). Herrera-Saldana et al. (1990) evaluated the effects of manipulating starch and protein sources on MCP flow to the duodenum in lactating dairy cows. In that study, dairy cows were fed diets synchronized for rapid ruminal degradation of starch and protein (barley [B] and cottonseed meal [CSM] as the principal sources of starch and protein, respectively, designated B-CSM) or slow ruminal degradation of starch and protein (milo [M] and brewers dried grains [BDG] as the principal sources of starch and protein, respectively, designated M-BDG) or unsynchronized diets (designated B-BDG or M-CSM). Both duodenal flow of MCP and the efficiency of MCP synthesis (expressed as g microbial N/kg truly fermented organic matter in the rumen) were greatest in the diet that was synchronized for rapid rates of energy and protein degradation (B-CSM) when compared to the diet that was synchronized for slow rates of energy and protein degradation (M-BDG) or the unsynchronized diets (B-BDG and M-CSM) (Figure 2). Similar observations of greater duodenal MCP flow and microbial efficiency in dairy cows fed diets synchronized for rapid (high-moisture shelled corn and canola meal) vs. slow (dry corn and blood meal) rates of energy and protein degradation in the rumen were reported by Aldrich et al. (1993) (Figure 3).

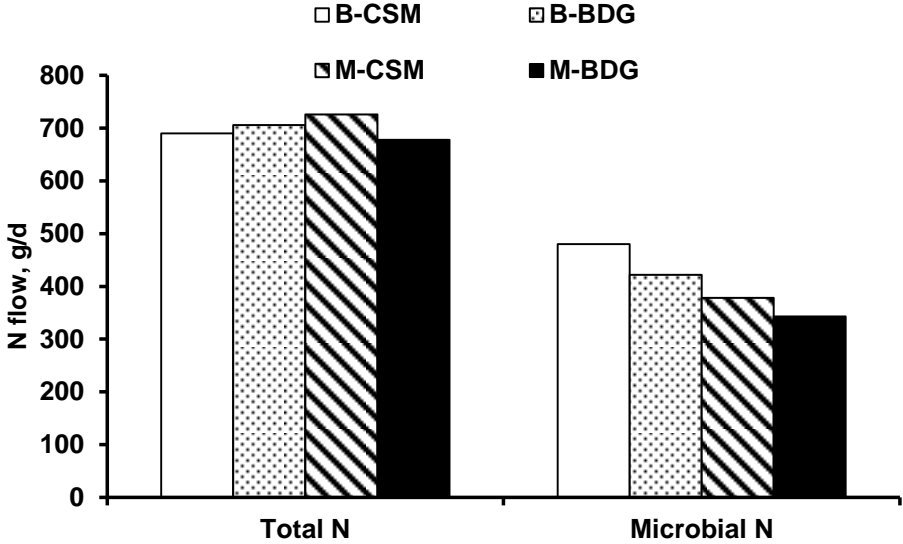
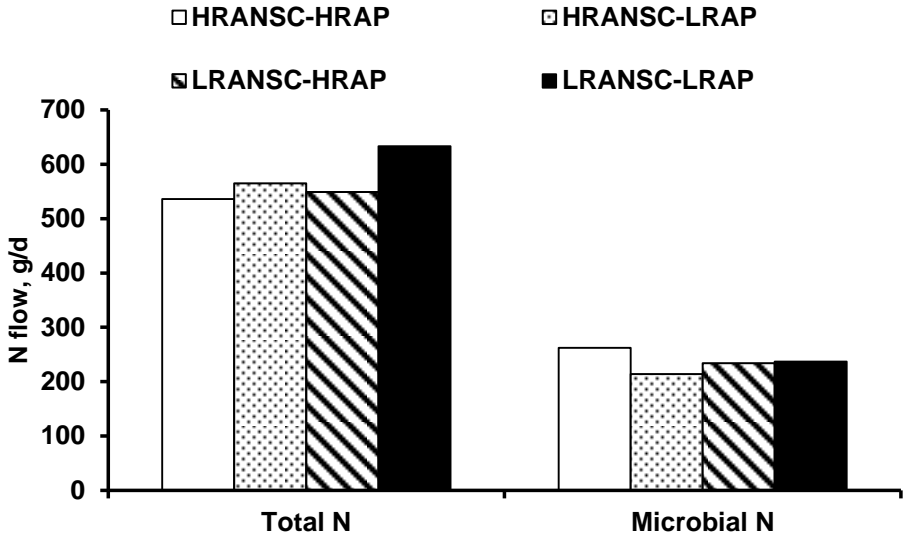


Figure 2. Effects of the synchronization of protein and starch degradation in the rumen on total nitrogen (N) and microbial N flow to the small intestine in lactating dairy cows. B = barley; BDG = brewers dried grains; CSM = cottonseed meal; and M = milo. Microbial N flow was greater ( $P < 0.05$ ) for B-CSM when compared to M-BDG, B-BDG and M-CSM. Data are from Herrera-Saldana et al. (1990).



**Figure 3.** Effects of the synchronization of protein and starch degradation in the rumen on total nitrogen (N) and microbial N flow to the small intestine in lactating dairy cows. HRANSC-HRAP = high ruminally-available non-structural carbohydrate and high ruminally-available protein; HRANSC-LRAP = high ruminally-available non-structural carbohydrate and low ruminally-available protein; LRANSC-HRAP = low ruminally-available non-structural carbohydrate and high ruminally-available protein; and LRANSC-LRAP = low ruminally-available non-structural carbohydrate and low ruminally-available protein. Microbial N flow was greater ( $P < 0.05$ ) for HRANSC-HRAP when compared with HRANSC-LRAP, LRANSC-HRAP and LRANSC-LRAP. Data are from Aldrich et al. (1993).

Whereas the above studies evaluated the effects of nutrient synchrony on ruminal N efficiency and MCP synthesis by manipulating both the energy and protein sources simultaneously, other studies have manipulated either the energy or the protein source independently. Because barley starch is more fermentable in the rumen compared to corn starch, a summary of research data from 16 published studies (Sauvant and van Milgen, 1995) indicated that duodenal MCP flow was increased by an average of 10% when sources of rapid ruminal starch degradation (e.g., barley) replaced sources of slow ruminal starch degradation (e.g., corn). Numerous studies have also investigated the effects of cereal grain processing on ruminal N efficiency and MCP synthesis (see review by Theurer et al., 1999). Processing of cereal grains (e.g., steam flaking) typically shifts the site of carbohydrate digestion from the small intestine to the rumen, thus increasing ruminal energy availability and, consequently, decreasing ruminal ammonia-N concentrations



and stimulating MCP production (Theurer et al., 1999). A summary of numerous studies conducted in the United States indicated that feeding steam-flaked corn or sorghum in alfalfa-based diets consistently improves rumen N use and MCP production in dairy cows compared to dry-rolled grain (Theurer et al., 1999). Data on the effects of barley grain processing on ruminal MCP synthesis is scarce. Feeding more extensively-processed barley compared to coarsely-rolled barley tended to increase MCP flow in dairy cows (Yang et al., 2000); however, it is not at all clear what the optimum degree of processing of barley is to maximize ruminal N use and MCP synthesis (Yang et al., 2000). It should be pointed out that MCP synthesis is not always stimulated by feeding more total carbohydrate or ruminally-fermentable carbohydrate (Dewhurst et al., 2000). In some feeding situations, increasing ruminal carbohydrate fermentation may suppress ruminal MCP synthesis by decreasing both ruminal pH and fiber digestion (Dewhurst et al., 2000).

A few studies have investigated the impact of dietary substitution of starch with sugars or intra-ruminal sugar infusions to increase ruminal energy availability on ruminal N efficiency and MCP synthesis. Because sugars are more rapidly fermented in the rumen than starch, substitution of starch with sugar may increase ATP availability, thus improving ruminal N use and allowing for more efficient MCP synthesis; however, perusal of the literature indicates that the effects on MCP production of replacing dietary starch with sugar have been equivocal. Intra-ruminal infusions of sucrose in dairy cows fed grass silage-based diets enhanced ruminal MCP production (Kim et al., 1999; Figure 4). Similarly, the substitution of starch with sugar in continuous culture increased MCP yield (Stokes et al., 1991). On the other hand, the substitution of starch with sucrose yielded less MCP in dairy cows (Sannes et al., 2002) and in *in vitro* incubations (Hall and Herejk, 2001). More recently, replacing dietary starch with sucrose in dairy cows fed mixtures of corn silage- and alfalfa silage-based diets did not affect MCP synthesis (Broderick et al., 2008).

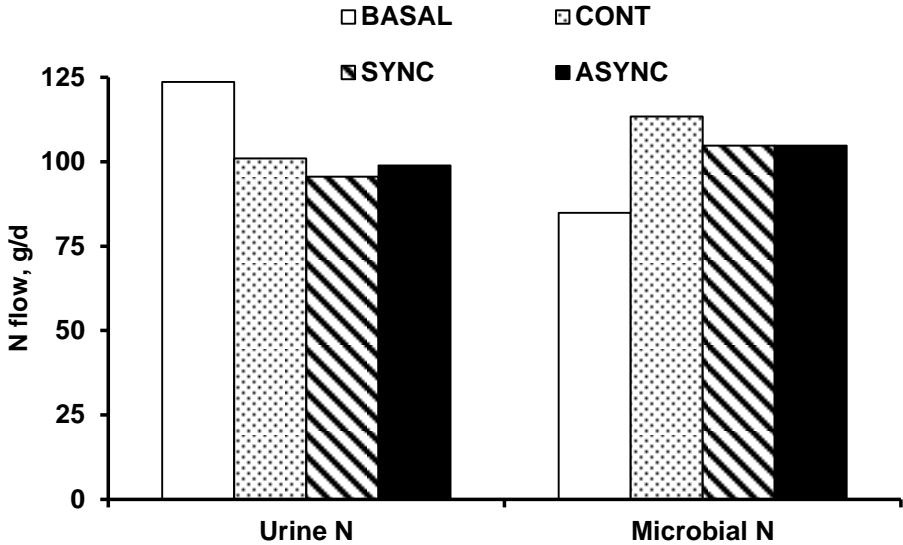


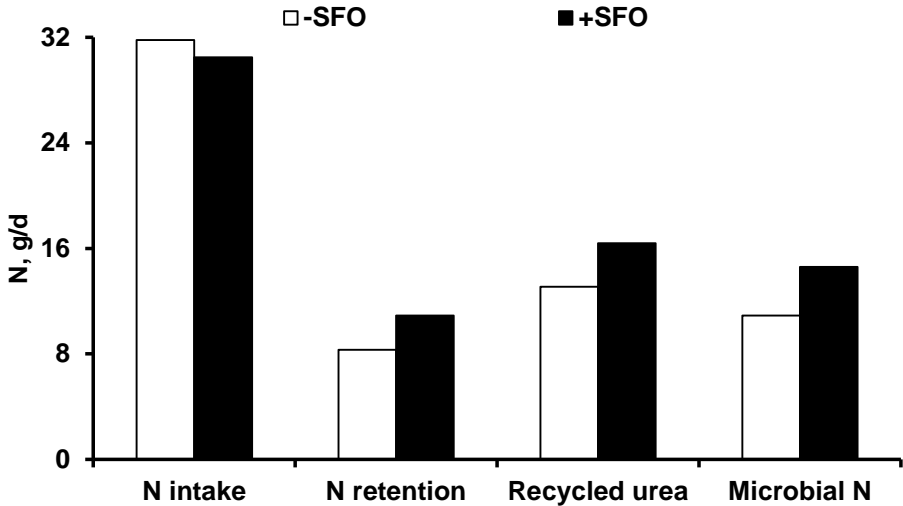
Figure 4. Urinary nitrogen excretion and microbial N flow to the small intestine (calculated using urinary purine derivative excretion) in non-lactating dairy cows receiving a basal diet of silage with or without (BASAL) intra-ruminal infusions of 1 kg/d sucrose given continuously (CONT), synchronously (SYNC; given as two 6-h intra-ruminal infusions starting at 1000 and 2200 h each d) or asynchronously (ASYNC; given as two 6-h intra-ruminal infusions starting at 1600 and 0400 h each d). Microbial N flow was greater ( $P < 0.05$ ) for CONT, SYNC and ASYNC when compared to BASAL. Data are from Kim et al. (1999).

### ■ Enhancing Urea Recycling to the Rumen Can Potentially Ameliorate Short-Term N Deficiencies in Asynchronous Diets

As previously discussed, urea that is produced in dairy cows from excessive ammonia-N absorption is largely excreted in urine. However, dairy cows have evolved a mechanism that allows the constant recycling of urea to the rumen where it can be used for MCP production. In dietary situations in which there is asynchronous nutrient supply due to a deficiency of RDP, urea that is recycled to the rumen can ameliorate any short-term N deficiencies. When greater amounts of total carbohydrate or ruminally-fermentable carbohydrate are fed, the increase in ruminal energy availability stimulates MCP production and, in addition, increases urea recycling to the rumen (Theurer et al., 1999). In dairy cows fed steam-flaked corn or sorghum, net transfer of urea to the rumen was increased by 80% (Theurer et al., 1999). Unfortunately, much less research is available on urea recycling to the rumen in dairy cows fed barley-

based diets that are typical of western Canada. Recently, my research group compared urea recycling in dairy cows fed dry-rolled or pelleted barley as the main carbohydrate source and our results indicated that urea recycling to the rumen tended to be higher in cows fed dry-rolled compared with those fed pelleted barley (Gozho et al., 2008). These results contradict previous observations with processed corn or sorghum, and we suspect that the more acidic ruminal conditions in cows fed pelleted barley could have impaired urea recycling to the rumen. Clearly, more research is necessary in dairy cows fed processed barley.

There is evidence that unsaturated fat supplements can have major effects on ruminal N efficiency and MCP synthesis, and these effects are partly mediated via the elimination of ruminal protozoa. Protozoa ingest bacteria and increase ruminal ammonia-N concentrations because they degrade both dietary and bacterial proteins. Recently, we fed linoleic acid-rich sunflower oil to sheep and substantially reduced protozoal populations within the rumen. More importantly, sheep fed sunflower oil had lower ruminal ammonia-N concentrations, retained more N, recycled greater amounts of urea to the rumen, and had greater amounts of MCP flow to the duodenum (Kiran and Mutsvangwa, 2011; see Figure 5). Much less research is available on fat supplementation in dairy cows and the impacts on ruminal N efficiency and urea recycling. A drawback of fat supplementation as a strategy to enhance ruminal N efficiency and MCP supply could be any associated milk fat depression which would be undesirable in our current quota system that is based on butterfat.



**Figure 5.** Nitrogen (N) intake, N retention, recycled urea and microbial N production (calculated using urinary purine derivative excretion) in sheep fed a basal diet with (+SFO) or without (-SFO) sunflower oil as a partial defaunating agent. N retention, recycled urea, and microbial N flow were greater ( $P < 0.05$ ) for +SFO compared to -SFO lambs. Data are from Kiran and Mutsvangwa (2011).

## ■ Conclusion

Microbial crude protein flowing out of the rumen to the small intestine is a major contributor to the MP requirements of dairy cows, and its essential amino acid profile closely matches that of milk protein. Some studies have reported beneficial effects in terms of increased MCP synthesis when dairy cows are fed synchronous diets that are matched in terms of ruminal energy and N availability. Nutrient synchrony can be achieved by manipulating both the energy and protein sources simultaneously or manipulating either the energy or protein source independently. However, it is clear from the contradictory results that are presented in the literature that achieving nutrient synchrony does not necessarily increase ruminal N efficiency and MCP synthesis. It has been suggested that when formulating dairy cow diets under practical conditions, the objective should be, firstly, to provide an even supply of energy as it is the major “driver” of MCP synthesis and, secondly, to ensure the supply of adequate amounts of RDP to meet microbial N requirements.

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