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Nutrient movements through ruminant livestock production systems

Adegbola T. Adesogan, Jose C. B. Dubeux and Lynn E. Sollenberger

ABSTRACT

Considerable attention has been paid to reducing nutrient emissions from ruminant livestock in the last few decades. This area will continue to attract considerable research in the future due to increasing farm sizes in some developed countries as well as the increasing demand for meat and dairy products, particularly in developing countries. This paper discusses the deposition and losses of carbon and nitrogen in soils and plants in grazed and harvested forage systems as well as utilization and losses of both nutrients by ruminants in both systems. The paper also outlines several soil, plant, and animal-focused strategies that can be used to reduce carbon and nitrogen losses from ruminant livestock systems. These strategies will become increasingly important due to the need to feed the growing population of the world while reducing environmental pollution from ruminant livestock systems.

Key words: Environment, Livestock, Losses, Mitigation, Nutrient

Introduction

The quantity and availability of nutrients in feeds ingested by ruminants directly determines their performance and the efficiency of utilization of such nutrients determines the profitability and environmental impact of the ruminant livestock production enterprise. Meat and dairy production account for almost half of the food-generated greenhouse gases (Beauchemin, 2015) and significant portions of the N emissions released as ammonia into the atmosphere and the nitrate losses in groundwater. Consequently, considerable attention has been paid to reducing nutrient emissions from ruminant livestock in the last few decades. This area will continue to attract considerable research in the future due to increasing farm sizes in some developed countries as well as the increasing global demand for meat and dairy products resulting from diet changes associated with increasing incomes and populations, and urbanization in developing countries.

This paper discusses nutrient flows from the soil to animal continuum in ruminant livestock systems and illustrates the differences in nutrient deposition and utilization in grazed and harvested forage systems. For each scenario, the paper identifies the main sources of nutrient losses and describes strategies for their mitigation. The focus is on carbon and nitrogen because of the fundamental role of these nutrients in livestock productivity, profitability and environmental stewardship.

Carbon deposition and utilization

Plants obtain C in the form of CO₂ from the atmosphere and convert it to carbohydrates via photosynthesis. The efficiency of light energy conversion of photosynthesis is only about 3% for C₃ grasses and 5-6% for C₄ grasses (Ball *et al.*, 2015). The major C pool in grassland ecosystems is soil organic matter (SOM). Soil organic C (SOC) occurs in different forms, with varying degrees of recalcitrance. Labile C forms are easily decomposed and they are found in freshly deposited organic

material. Soil microorganisms are the transforming agents linking senescent plant material C to stable SOM. As microorganisms decompose plant material and eventually die, microbial C stabilizes forming a matrix with clay minerals in soil, protecting it from decomposition (Cotrufo *et al.*, 2013). Through soil microbial processing of plant-derived organic matter, a long-term reservoir of nutrients accumulates, and their gradual mineralization avoids loss to surface or ground water (Franzluebbers, 2008). Additionally, soil aggregates are built to store more water for plant uptake and to withstand degenerative forces of erosion and compaction. Thus, it can be concluded that SOM is an ecological cornerstone, providing C storage, nutrients to plants, stability and water-holding capacity to soil, and energy to microorganisms (Sollenberger *et al.*, 2012).

The soil contains 30 to 50×10^{11} Mg C compared with 7×10^{11} and 4.8×10^{11} Mg in the atmosphere and in plant-animal biomass, respectively (Stevenson and Cole, 1999). Although vegetation and grazing animal pools contain less C than the SOM, they play an important role in the cycling of C within pasture systems through surface litter deposition and decomposition, excreta return, and methane emission. Soil organic C accumulates in the SOM because of a balance between C inputs and C losses from the system. Carbon input is dependent on net primary productivity (NPP) of the agroecosystem. Thus, management practices that increase NPP lead to greater C input. Examples of these practices include fertilization, irrigation, improved cultivars, diversification of functional plant groups, and species richness (Tilman *et al.*, 1997; Dubeux *et al.*, 2007). Carbon losses occur through multiple processes including soil erosion, microbial respiration of plant litter, mineralization of SOM, respiration and

microbial activity during forage conservation, and through methane emissions by livestock.

Carbon deposition in plants and soils in grazed forage systems: Carbon inputs to grazed forage systems occur via plant photosynthesis, and C partitioning to root and shoot is critical in determining how fast C cycles. Shoot C is exposed to defoliation by grazing ruminants, to losses via animal fermentation and metabolism, and to leaching and volatilization losses following excreta deposition. These processes result in greater CO₂ evolution compared with initial allocation of C to below-ground biomass. As is true for harvested forage systems, below-ground plant material plays a major role in C addition to the soil in grazing systems. Grasses with deeper roots add C to the soil, particularly when associated with forage legumes (Fisher *et al.*, 1994). Saraiva *et al.* (2014) observed soil C stocks (0-1 m depth) of 214 and 358 Mg/ha for elephant grass (*Pennisetum purpureum* Schum.) and signal grass (*Brachiaria decumbens* Stapf.), respectively. The greater soil organic C stock for signal grass was attributed to Al tolerance, allowing development of roots deeper in the soil profile. In the southeastern USA, Pensacola bahia grass (*Paspalum notatum* Flugge) is well suited to increase SOC because it allocates a large proportion of photo assimilates to below-ground biomass (Interrante *et al.*, 2009).

Approximately 22% of global soil C stores are under grassland and as much as 90% of C stored in grassland ecosystems is below ground (Soussana *et al.*, 2004). Grazing lands typically have greater SOM than croplands due primarily to lack of tillage and to the predominant use of deep-rooted perennial plants in grazing lands (Franzluebbers, 2005). Grazed forage systems typically increase SOC at a faster rate than harvested forage systems. For example, during the first 5 yr of bermuda grass [*Cynodon dactylon* L. (Pers.)]

management, SOC increased an average of 1.4 Mg/ha/yr under grazing compared with 0.3 Mg/ha/yr for harvested forage (Franzluebbers, 2007). Greater accumulation of soil organic C with grazing was due to fecal return directly on the pasture rather than application elsewhere as with hay harvest. A 12-yr grazing trial on Coastal bermuda grass and bermuda grass over seeded with tall fescue [*Lolium arundinaceum* (Schreb.) S.J. Darbyshire] showed SOC was greater at moderate to heavy stocking rates compared with non-harvested or hayed forage at the end of 5 yr (Franzluebbers and Stuedemann, 2005), and the differences were even more pronounced at the end of 12 yr (Franzluebbers and Stuedemann, 2009). The presence of the grazing animal affects decomposition processes by trampling, excreta deposition, redistribution of soil nutrients via excreta return, and modification of chemical composition of the ingested plant tissue. These factors combine to enhance nutrient cycling and in many cases increase SOC (George *et al.*, 2013).

Carbon deposition in plants and soils in harvested forage systems: In harvested forage systems, C deposition occurs via above- and below-ground crop residues. Harvesting intensity and efficiency determine the amount of above-ground C returned to the soil as litter (Thomas, 1992). The importance of litter C increases as NPP increases (Lira *et al.*, 2006), but for harvested systems below-ground biomass is a more important contributor to soil C than above-ground biomass. Defoliation intensity is an important determinant of below-ground biomass because as defoliation intensity increases, below-ground biomass generally decreases. In addition to residue quantity, residue quality also plays a major role in SOM formation. More rapidly degradable litter leads to more efficient SOM formation due

to less CO₂ evolved, in contrast with highly lignified material where decomposition takes longer and fewer microbial products are formed (Cotrufo *et al.*, 2013). Because microbial products from litter decomposition are the main precursors of stable SOM, crops with lower C: N ratio (e.g., forage legumes) promote faster SOM formation due to their more efficient use in producing microbial products. Litter decomposition rate depends on the source material and environment, but total decomposition is commonly 50-70% per year for freshly deposited litter contrasting with 2-5% per year observed for stable SOM (Dubeux *et al.*, 2007). The latter represents the major soil C reservoir and plays a major role in the global C cycle.

Carbon losses during preservation of harvested forages: Considerable amounts of CO₂ can be lost from harvested forages due to continued plant respiration. This process is only inhibited in hays after the forage moisture and water activity decrease substantially, or in silages after anaerobic conditions prevail in the silo. In addition, CO₂ losses occur during heterolactic primary fermentation of glucose to acetic and butyric acids as well as during secondary fermentation of lactic acid to volatile fatty acids by silage bacteria. These C losses reduce DM recovery and they can be further increased by yeasts, which oxidize sugars and lactic acid to CO₂ or ferment sugars to ethanol during the silage feed out stage.

Carbon utilization by ruminants: In ruminant animals, C is ingested in several forms including fats, carbohydrates, and proteins, converted into various intermediates before being absorbed and either used for maintenance or performance or incorporated into tissues or excreted. Each of the ingested forms of C has different degradation rates and fates and utilization efficiencies. It is beyond the scope of this paper to consider each of the

C forms separately. Rather C transformations will be described in the context of energy utilization in this paper.

Of the gross energy ingested by ruminants the main avenues of losses are fecal, urinal, gaseous and heat. Fecal energy losses account for most of the losses and they are generally inversely proportional to forage digestibility. Consequently, factors that increase digestibility typically increase energy utilization and feed efficiency, and reduce energy losses to the environment. Urine energy losses are usually associated with urea excretion due to nutrient metabolism and they are important because of potential volatilization of ammonia formed from the urea. Methane energy losses have attracted a lot of attention in the last few decades because of their implications for energy utilization and performance as well as their contribution to climate change.

Ruminant utilization of carbon from grass versus harvested forages: Making hay from grass may reduce the DM digestibility of the forage, particularly if drying is prolonged (Milford and Minson, 1968; McDonald and Edwards, 1976). Whereas, studies indicate that ensiling grass has little to no effect on DM digestibility (Harris and Raymond, 1963; Cushnahan and Mayne, 1995), energy digestibility may be affected. Beever *et al.* (1971) fed sheep fresh ryegrass (that had been frozen and thawed), dried grass, or wilted or unwilted silage prepared from the same sward. They noted that drying grass did not affect the apparent digestibility of gross energy, cellulose, or hemicellulose. However, ensiling unwilted grass resulted in greater digestibility of gross energy, cellulose and hemicellulose than those of the fresh grass. The greater energy digestibility of the silage was attributed to the greater caloric value of the silage, which contributed to a greater gross energy intake.

The acidity achieved by ensiling may have also made the silage cell walls more digestible than those of the grass.

Drying and ensiling grasses have increased urinary energy losses (McDonald and Edward, 1976). Drying and ensiling forages also increased energy losses as methane in some studies (McCGrham, 1964; Herrman *et al.*, 2011) but not others (McDonald and Edward, 1976; Krueger *et al.*, 2011). The differences may be due to variations in aspects of the conservation process as well as whether or not corrections were made for volatiles lost during oven drying of silages (Krueger *et al.*, 2011). Methane (and nitrous oxide) production per unit of animal product is greater and efficiency of feed utilization is lower in intensive production systems (e.g. with higher yielding cows fed harvested forages and concentrates) versus extensive systems (lower yielding cows on pasture) (Reynolds *et al.*, 2011). However, the difference is unlikely to persist when cows with similar genetic potential are fed the same grazed or harvested forage in both systems. This is because the greater energy efficiency of animals in intensive systems is largely due to increases in yield per animal, which dilutes the energy cost of maintenance (Capper *et al.*, 2009).

Carbon retention

Improving C retention in plants and soils in grazed forage systems: Management practices to reduce plant and soil C losses from grazed systems are directly related to grazing management. Because overgrazing depletes the root system, reduces NPP, and may cause plant death, finding equilibrium between stocking rate and herbage mass is critical. Overgrazing also increases the likelihood of soil erosion resulting in loss of SOM and release of stored C to the atmosphere (Vågen and Winowiecki, 2013). In the long-term, optimizing grazing

pressure will contribute to long-term pasture persistence, reducing the need for pasture renovation. Minimizing the frequency of pasture renovation is critical because during this process, soil C is usually lost because tillage breaks down soil aggregates that protect SOM, exposing it to decomposition, and soil erosion is more likely (Sparovek *et al.*, 2007).

Improving C retention in plants and soils in harvested forage systems: Reduced tillage or no-tillage is the single most important management practice that will minimize SOC losses in harvested forage systems. Reduced tillage, however, requires proper equipment that may be too expensive for some producers. Long-term results in terms of increased SOM and benefits for the crop and ecosystem, however, are often worth the investment. Combining reduced-tillage with other agronomic practices such as the use of crop rotation and cover crops to reduce soil erosion is an effective way to improve overall soil properties, reducing C losses (Villamil *et al.*, 2006). Integration of cattle into a sod-based crop rotation can also have a significant positive impact on the system, making better use of the resources available year-round (George *et al.*, 2013). These authors observed greater levels of soil P, K, and SOC for grazed vs. non-grazed plots in a sod-based rotation system. Thus, integration of grazing and sod-based rotation in cropping systems benefits productivity of the following crops and improves soil properties. In general, practices that enhance above- and below-ground litter deposition in forage harvesting systems coupled with practices that reduce decomposition (e.g., no-till) should lead to greater soil C in the long-term.

Improving C retention in harvested forages: Carbon and energy losses from hays can be reduced by rapidly drying the grass immediately after cutting, spreading wide thin

layers of grass in windrows and tedding as appropriate, using mechanical processors or chemicals to aid water loss, and harvesting as early as possible after the morning dew disappears on dry, low-humidity days. Carbon losses from silage can be reduced by filling and sealing silos immediately after harvesting to reduce aerobic respiration, using chop lengths that optimize packing, aiming for a packing density of 650 kg of fresh matter/m³, and using plastic films that impede oxygen infiltration. In addition, preservatives like ammonia, propionic acid and sorbate or benzoate salts can reduce C losses from ensiled forages. Likewise, homolactic bacteria and *L. buchneri* can reduce C losses during ensiling and feedout, respectively.

Improving C retention in ruminants: One of the most effective methods of increasing the level and efficiency of C and energy utilization by ruminants is to increase the digestibility of the forage. This can be achieved in a variety of ways including selecting for low-lignin (brown-midrib) or low-ferulic acid forages, harvesting at maturity stages that optimize nutritive value, and by using physical processing to increase starch digestibility or rupture the plant cell walls or to reduce their particle size. In addition, digestibility of structural carbohydrates can be increased by yeast supplementation or by fibrolytic enzyme treatment, and proteolytic enzymes can be used to increase starch digestibility.

Energy losses as methane can be reduced by increasing animal productivity, inhibiting ruminal methane synthesis with nitrates or ionophores; improving fiber digestibility with enzymes, ammonia or by genetic selection; by targeted supplementation with fats, or strategic management (grazing management, legume incorporation into the sward, or reducing age at slaughter). In addition, the efficiency of energy utilization can be increased by selecting

for more efficient animals (low residual feed intake), ensuring animal health and welfare, precision feeding, increasing the reproductive rate, provision of adequate lighting, avoiding heat stress, and reducing activity. Carbon losses due to refusals can be reduced by feeding total mixed rations, cleaning feed bunks regularly, and preventing feed spoilage. Feed wastage-associated C losses can be reduced by using hay rings and similar devices and ensuring proper feeder design and dimensions for the type of animal.

Nitrogen deposition and utilization

Considering all terrestrial ecosystems, the atmospheric N pool is 16,000 times greater than the sum of the soil and biotic N pools (Russelle, 1996). In grasslands, the soil is the second largest N pool and is affected by SOM, soil microbial biomass, fixed NH_4^+ , and to a lesser extent, the plant-available inorganic N (Stevenson and Cole, 1999). The atmospheric N pool is available to plants only through biological N fixation, mediated by free-living or plant-associated bacteria. Grasses having the C4 photosynthetic pathway generally have lower herbage N concentrations than C3 plants, and they produce approximately twice as much biomass per unit of N uptake than C3 grasses (Moore *et al.*, 2004). Greater C:N ratio of C4 grasses affects their litter quality, decomposition by microbes, and utilization by livestock.

Nitrogen losses can be significant from forage-livestock systems, reducing efficiency of N utilization. They occur through a number of pathways including leaching and volatilization of fertilizer N, denitrification in soil, and N_2O emission from livestock waste. Bouwman *et al.* (2002) indicated that N_2O and NO emissions also accompany N fertilizer application. The IPCC (2006) suggested that for every 100 kg of fertilizer N added to the

soil, on average 1 kg of N is emitted as N_2O . When animals consume N in forage-based diets, 75 to 95% of the N ingested is excreted in feces and urine, resulting in only a small percentage removed from the system in meat or milk (Whitehead, 2000). Nutrients excreted in dung and urine are more susceptible to loss than nutrients in plant litter (Dubeux *et al.*, 2007), thus nutrients returned to harvested or grazed fields in livestock manure are subject to significant losses. Nitrogen is excreted in both dung and urine with the proportion being a function of diet N concentration, but urine is the dominant source of gaseous N losses because urine N is not stabilized by slowly mineralized C compounds, as is the case for at least half the N in dung (Mathews *et al.*, 2004).

Nitrogen deposition in plants and soils in grazed forage systems: The profound differences in N cycling between grazed and harvested forage systems are because of the much lower N removal amounts from grazed systems, alluded to earlier, and the effects of N return in animal excreta. Return of excreta by livestock in Georgia, USA, resulted in soil inorganic N and extractable P, K, and Mg concentrations that were somewhat greater with grazing vs. no defoliation, but they were much greater with grazing than with hay harvest (Franzluebbers and Stuedemann, 2009). Similar results have been reported in Florida, USA by Mathews *et al.* (1994a). Nutrient cycling within the pasture makes it possible to avoid the high demand for continuous nutrient input that is associated with hay harvest (Mathews *et al.*, 1994a; Franzluebbers, 2007).

Haynes and Williams (1993) reported that although excretal patches in grazed systems may cover only 30 to 40% of the pasture surface annually, the associated high nutrient input stimulates herbage growth, and these areas may contribute up to 70% of the annual pasture

production. In Colorado, USA, urine patches affected only 2% of the pasture surface, but they contributed 7 to 14% of consumed forage (Day and Detling, 1990). In a Florida, USA study, deposition of dung had no effect on N harvested in forage; however, N harvested increased linearly from 48 to 88 kg/ha as urine application frequency increased from 0 to 3/year (White-Leech *et al.*, 2013a). Nitrogen recovery in harvested above-ground biomass from urine application was small but positive, but it decreased from 12.4 to 7.4% as urine application frequency increased. Forage protein and digestibility were not affected by dung application, but they increased with increasing urine application frequency and for distances up to 30 cm from the edge of the urine deposit. Urine increased dry matter harvested for e⁻⁸⁴ d and increased crude protein for e⁻²⁸ d following a single urine application and e⁻⁸⁴ d after multiple applications (White-Leech *et al.*, 2013b).

There are limits to the benefits associated with excreta return because although 75-95% of N consumed is excreted back on to the pasture, volatilization and leaching losses are significant and deposition patterns are far from uniform. Uniformity of deposition can be affected by weather conditions, placement of feed, water, and shade, and by grazing management (Mathews *et al.*, 1994a; Mathews *et al.*, 1996). Mathews *et al.* (1994a) showed that location of shade and water is more important than grazing method in determining nutrient redistribution in a warm climates. In later work, Mathews *et al.* (1996) showed that position of shade has a greater impact than position of water. Because of the concentration of nutrients, soil N losses (e.g., ammonia volatilization, N leaching) likely increase in areas where cattle congregate. Partitioning of N between feces and urine depends on dietary N concentration. As N in the diet increases, a

greater proportion of N will be excreted via urine (Dubeux *et al.*, 2007). Fecal N is found mostly in organic forms such as protein, amino acid, peptides, or bound to fiber components. Urine N occurs mostly as urea (Bristow *et al.*, 1992) which is partially lost as volatilization of ammonia, especially in warm and moist environments. Dung pats have an outer aerobic layer and inner anaerobic portion. In the inner portion, N denitrification can occur due to low oxygen tension, increasing N losses. Dung beetles aerate the dung pat and incorporate dung into the soil, helping to reduce N losses.

Nitrogen in grazed pasture also cycles in senescent ungrazed forage (litter). Grazing pressure shifts the balance between N return via excreta and litter, with more N lost under overgrazing due to a greater proportion of N returned as excreta. Overgrazing also depletes the root system, leaving the pasture more prone to N leaching losses. Litter N is less prone to losses than urinary N, therefore, overgrazing can lead to soil N reduction because of increased N losses. Piñeiro *et al.* (2010) observed an increase in SOM C:N ratio of grazed areas compared with paired non-grazed areas. The authors attributed the difference to greater N losses in grazed areas.

Nitrogen deposition in plants and soils in harvested forage systems: Nitrogen flow in harvested forage systems differs from grazed systems because the animal is not involved in the nutrient recycling process at the site where the plant is produced. In harvested systems, forages are usually uniformly cut, either by harvesting machinery or, in small farming systems, using hand tools such as machetes. Mechanically harvesting forage and feeding it elsewhere removes most nutrients in above-ground herbage mass, thus most of the plant N that returns to soil is from unharvested above-ground residue and decaying roots. Considering several forage species commonly

used for hay, N removal in harvested biomass ranged from 150 to 315 kg/ha (Ball *et al.*, 2015). In contrast, N removal in animal product is quite small from grazed pasture; the body of a 225 kg calf might contain ~12 kg of N. Thus, fertilizer requirements for harvested forage systems are much greater than for grazed systems. Legumes can provide N to associated grasses, but in harvested systems the return in excreta is not operating. Early in stand life, legume N transfer to associated grasses by other means is small, averaging only 6% of total grass N in Year 1 of harvesting several grass-legume mixtures (Heichel and Henjum, 1991). Apparent N transfer to grass averaged up to 47% in later years, with an average of 25% or 10 to 20 kg N/ha/yr in Years 2-4. Most N transfer from legumes as stands age occurs due to nodule or root sloughing by the legume or plant death. With the annual legume *Aeschynomene americana* L.), Sollenberger and Quesenberry (1986) found high correlations ($r > 0.80$) between percentage legume and CP concentration of the associated grass due to leaflet drop by the legume before harvest.

The amount of above-ground material that will return to soil depends on harvesting intensity and efficiency of harvesting equipment. Unharvested material might include residues with high C:N ratio, usually the base of the plant, but as noted earlier it may also include leaves shattered during the harvesting process, with lower C:N ratio. Unharvested plant residues and roots will decay over time, with decomposition rate interacting with biotic and abiotic factors. Nitrogen released by above- and below-ground litter decay can be taken up by plants, captured by the microbial population, bound to clay particles (NH_4^+), or lost from the system by leaching, denitrification, or ammonia volatilization. After undergoing initial

decomposition, recalcitrant N is bound to SOM and can be protected by different physical and chemical mechanisms (Six *et al.*, 2002).

Nitrogen losses during preservation of harvested forages: Leaf N losses can be significant when hay is made from broad-leaved legumes, particularly if poor drying techniques are used or if rainfall causes nutrient leaching. Beever *et al.* (1971) noted that depending on the temperature and duration of drying, and on the nature of the forage protein, drying grass (haymaking) might denature and reduce the solubility of protein, decrease ruminal proteolysis, increase microbial protein synthesis, and decrease N digestibility.

In ensiled forages, plant enzymes degrade plant true protein via proteolysis into non-protein nitrogen (NPN) including peptides and amino acids. In addition, amino acids in silages are deaminated into ammonia and branched-chain VFAs or degraded into biogenic amines and amides by microbial activity (McDonald *et al.* 1991). This breakdown can be extensive and the resulting NPN can account for up to half of the crude protein in certain forage legumes. Proteolysis and deamination make silage protein highly soluble, rapidly degraded in the rumen, and inefficiently used by ruminants; therefore, it can contribute substantially to environmental pollution (Charmley, 2003). In addition, the nitrous oxide formed during ensiling by bacterial nitrate degradation is a toxic and potent greenhouse gas. Furthermore, spoilage of silage by yeasts and molds may lead to further degradation of plant protein into forms that are readily lost to the environment.

N utilization in ruminants: Though ruminants can synthesize high-quality microbial protein from non-protein N or use low-digestibility forages as an energy source via their ruminal

microbes, they are also inefficient utilizers of high-quality N because the same ruminal microbes can decrease the quality of ingested high-quality protein. An average US dairy cow consumes 26 g of N/kg DM and excretes about 72% of the N it ingests (Weiss, 2014). Higher N excretion levels of 75 to 85% have been reported for feeding systems in which higher levels of N were fed (30 to 35 g of N/kg DM; Tamminga, 1992). Broderick (2005) noted that in housed (harvested forage) dairy cow systems, most of the inefficiently used N is not returned to the soil as only about 30% of the manure produced by dairy cows annually in the US is recovered and applied to cropland (Kellogg *et al.*, 2000). In addition, about 25% of dairy manure N is lost as ammonia (Pinder *et al.*, 2003). These statistics highlight the need to increase efficiency of N utilization on dairy farms especially because of the trend to overfeed N, the linear increase in manure N with dietary N intake, and the increasing size of the average US dairy (Broderick, 2005).

The main N losses in urine include those due to urinary excretion of urea arising from ammonia lost from the rumen; urinary N from indigestible or endogenous N, and urinary N resulting from inefficient use of absorbed protein for maintenance and performance (Tamminga, 1992). Urinary N losses are more problematic than fecal losses from an environmental standpoint because they are more rapidly volatilized, due to urea conversion to ammonia by urease. In addition, urine N is more rapidly converted to nitrate N and incorporated into the soil N pool. Factors that increase manure N output include overfeeding protein, increasing dry matter intake, feeding diets with high silage proportions, or those with excessive ruminally degradable protein (RDP) contents, or unmatched or asynchronous ruminally fermentable energy and RDP sources.

Ruminant utilization of N from grass versus harvested forage: Concentrations of NPN in silages are much greater than those in the grasses from which they are made. Volden *et al.* (2002) reported that ensiling first-cut grass pasture increased the buffer-soluble N concentration from 23.3 to 65.3%. This was largely because concentrations of small-chain peptides, free amino acids and ammonia were increased by about 25, 20 and over 600%, respectively by ensiling. Due to the lower concentration of soluble NPN compounds in grasses than the corresponding silages, microbial N synthesis is higher and urinary N losses are less when grass is fed instead of grass silage. Siddons *et al.* (1985) reported that when low-N dried grass was fed to lambs instead of high-N silage, feeding the silage led to a higher concentration of ammonia in rumen fluid, a higher rate of irreversible loss of ammonia from the rumen, lower ruminal microbial protein synthesis, higher rate of absorption of ammonia across the rumen wall, higher plasma urea concentration, higher urea synthesis rate, and higher urinary urea excretion. These outcomes were due partly to the different N concentrations that were fed but also to the high soluble NPN concentration of the silage and its asynchronous energy and protein supply. Cushnahan *et al.* (1995) compared effects of feeding fresh grass or grass silage from the same sward, which had undergone an extensive or restricted fermentation. Feeding both silages instead of the grass increased the soluble N fraction, reduced the potentially degradable N, and increased urinary N losses but values of the latter were greatest when the extensively fermented silage was fed.

Legumes are often incorporated into grass pastures to increase CP intake and hence performance. However, Poppi and McLennan (1995) reported that though tropical legumes increase N intake in tropical pasture systems,

they typically do not increase intestinal protein supply per unit of DMI to the same extent if at all due to protein loss in the rumen. Consequently, they noted that unless tropical legumes can increase total DMI by at least 30%, they would not supply sufficient intestinal protein to increase live weight gain of beef cattle by about 300 g/d.

Nitrogen retention or recapture

Increasing N retention/recapture in plants and soils in grazed forage systems: Adjustment of stocking rate and grazing pressure are important management practices to reduce excreta N losses and to achieve an appropriate balance between N cycling in plant litter and excreta (Thomas, 1992). Adjustment of grazing pressure also balances the C allocation to shoot and root (Richards, 1993), maintaining a developed root system which is important for capturing soil mineral N (Tinker and Nye, 2000). Management strategies that improve excreta distribution reduce soil N losses. Dubeux *et al.* (2014) observed that stocking method affected soil N, with continuous stocking presenting greater soil mineral N in high traffic areas than rotational stocking with short grazing periods. This occurred because livestock congregate under shade and around water points, concentrating dung and urine in these areas, especially under continuous stocking. This effect was reduced with rotational stocking with short-grazing periods because animal were forced to spend time across the entire pasture. Decreasing nutrient recovery with increasing frequency of urine application and decreasing dry matter harvested with increasing frequency of dung application (White-Leech *et al.*, 2013a) suggest that in low-input grazing systems, where most nutrients are cycling in plant litter or animal excreta, grazing strategies that increase uniformity of excreta deposition may be of

significant value. Rotational stocking with short occupancy periods has been reported to be one such practice (Dubeux *et al.*, 2014). In addition, attention should be paid to the positioning of shade and water in the pasture because in warm climates or during warm seasons their effects on animal distribution in the landscape are much greater than those of grazing management. Attention to diet composition is also important, as balance and synchrony between rumen degradable protein (RDP) and digestible energy also reduces urinary N losses, particularly under high N nutrition (Moore *et al.*, 1999; Richard *et al.*, 2005).

Increasing N retention/recapture in plants and soils in harvested forage systems: Major N losses from harvested forage systems occur via leaching, denitrification, and ammonia volatilization. Leaching occurs when N moves below the root zone and eventually encounters ground water. Soil texture affects infiltration rate, and sandy soils are more prone to leaching than clay soils. Optimal conditions for leaching include the combination of sandy soils, high soil mineral N, intensive rainfall (or mismanagement of irrigation), and crops with shallow root systems. Management practices that can be used to reduce leaching include split applications and use of slow release N fertilizer, irrigation management based on crop coefficient (Kc) and soil water balance, and nitrification inhibitors (Soares *et al.*, 2012). In acidic soils with Al toxicity, application of gypsum often promotes deeper rooting (Ritchey *et al.*, 1980). Deeper root systems reduce N leaching and improve overall N-use efficiency (Bowman *et al.*, 1998). Denitrification is another pathway of soil N loss. Denitrification occurs in the presence of denitrifying microorganisms, soluble C and N oxide, and low oxygen tension. Efficient drainage systems and use of ammonium-based

fertilizer reduce denitrification in harvested fields. Ammonia volatilization occurs when urea fertilizers or animal manure are applied at soil surface. Volatilization increases under warm and moist conditions, presence of plant residues that enhances urease activity, and alkaline soil environment (Wang *et al.*, 2004). Incorporation into the soil of urea fertilizers and manure and irrigation immediately after application reduces ammonia volatilization. Use of other N-fertilizer sources such as ammonium sulfate or ammonium nitrate as well as urease inhibitors also reduces N losses through volatilization (Soares *et al.*, 2012). Soil tillage reduces SOM protection by disrupting soil aggregates, increasing SOM decomposition rate and the release of N as NH_4^+ which is rapidly oxidized to nitrate. Because nitrate is more prone to leaching, soil tillage often increases soil N loss. Thus, no-till is an important management practice to conserve soil N, reducing its loss to the environment.

Improving nitrogen retention during preservation of harvested forages: To improve retention of N in harvested and wilted forages, it is important to use the same excellent management practices for increasing C retention in hays. In addition, it is necessary to store hay bales in a barn or under plastic to reduce N losses due to leaching by rainfall. In ensiled forages, N retention can be increased by increasing the rate of acidification of the silage to reduce the growth of the N-degrading *clostridia* and *enterobacteria* that thrive before the pH drops below 5. This can be achieved by inoculation with lactic acid bacteria like *L. plantarum*, propionic and other acids. Tannins can also be used to reduce ensiling and ruminal proteolysis and thereby increase N utilization efficiency, but they are only useful if the bound protein is released and digested in the hindgut. Selection of forages with high

polyphenol oxidase activity can reduce ensiling and ruminal proteolysis via N-binding during the browning reaction (Lee, 2014). Additives that inhibit spoilage yeasts and molds like propionic acid, and *L. buchneri* can also enhance N retention by preventing its degradation to ammonia at silage feedout. In addition, adopting excellent silage management practices like compacting adequately, sealing immediately and feeding out at a high rate (at least 15 cm) daily, will help prevent silage spoilage and the associated N losses.

Improving nitrogen retention in ruminants: To reduce ruminal N losses from pasture legumes that can increase urinary N losses, Poppi and McLennan (1995) recommended: 1) strategic use of energy supplements that match the ammonia release in the rumen from the legume to improve ruminal N utilization, 2) using legumes that increase both energy and protein supply, and 3) strategic reduction of the ruminal degradability of the legume for instance by using legumes with sufficient tannins to ensure ruminal bypass of protein without interference with intestinal absorption.

One of the most effective strategies to increase N retention in ruminants is to reduce N intake. Various studies have shown that reducing dietary N intake to a critical value (about 25 g/kg DM for lactating dairy cows) considerably reduced manure N losses (Tamminga, 1992; Broderick, 2005). Further reductions in N intake may reduce the performance of cattle unless supplementary protected amino acids like methionine or its analogs are fed. Overfeeding N can also be avoided by precision or phase feeding the herd, i.e. grouping animals by performance and feeding them different levels and sources of N accordingly. Split sex feeding can be combined with phase feeding to achieve similar benefits

in beef cattle or small ruminants. Nitrogen utilization efficiency can be further improved by using nutritional models to match RDP sources to rumen fermentable energy sources and to balance the ration for amino acids. Nitrogen losses may also be reduced by frequent sampling of ingredients to enable prompt adjustments to the formulation of the diet that will optimize N utilization efficiency. Furthermore, strategies that increase ruminal microbial protein synthesis will likely reduce manure N losses. These include feeding high-sugar grasses (Merry *et al.*, 2006), increasing the ruminal starch supply and availability by supplementing with starch sources like ground corn or corn silage, processing to reduce the particle size of cereal grains or to rupture the kernel of corn, and adding supplemental proteases to degrade the protein matrix enclosing the starch in corn kernels. Reducing intake of excess RDP is particularly important as it can reduce the attendant urine N and energy losses. Such problems can be reduced by replacing dietary silage with hay or fresh grass, reducing the ruminal degradability of dietary protein by tannin supplementation, by heat, solvent or expeller treatment or by replacing dietary RDP with rumen-undegradable protein sources or slow-release N sources like encapsulated urea.

Conclusions

The deposition and utilization of C and N differ markedly in grazed and harvested livestock systems. In the latter, more nutrient losses are likely and there is less return of removed nutrients to the soil. Nevertheless, harvested forages are essential for year-round feeding of housed ruminants, for sustaining ruminants during winter or dry seasons and for providing sufficient nutrients to ruminant livestock where pasture availability is limited. Several soil, plant, and animal-focused

strategies can be used to reduce C and N losses from ruminant livestock systems. These strategies will become increasingly important due to the need to feed the growing population of the world while reducing environmental pollution from ruminant livestock systems.

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