Pasture Nitrogen Flow

Nitrogen Flow in Intensively Grazed Pasture Systems

Michael Russelle

Introduction

Pastureland comprises about 72 million acres in the humid eastern one-half of the USA, and there is evidence that many pastures are being managed more intensively (e.g., Undersander et al. 1993). Pasturing generally is thought to be benign in terms of environmental impact, unless grazing is poorly managed, but this conclusion is based largely on measurements in mown perennial forages. For example, it is common to find that nitrate-nitrogen (NO_3-N) concentrations in soil or leachate under perennial hay crops are lower than under annual crops (Kollenbrander 1981). However, grazing by large herbivores alters the N balance of grassland. Increasing awareness of agriculture's impact on the environment in the late 1960's and early 1970's prompted research in Europe and New Zealand on the environmental impacts of intensive animal production on pasture. This review is based primarily on research results from those countries, because there is little data from North America.

Content

N Inputs and Transformations

Nitrogen enters a pasture primarily as fertilizer (when applied), symbiotic dinitrogen (N_2) fixation, supplemental feed (via manure), and atmospheric deposition; it leaves the field by a variety of pathways, some of which are desirable, such as in milk, meat, and wool, and some of which are undesirable, including leaching of NO_3 ions, runoff of particulate or dissolved N, or gaseous losses through denitrification or volatilization (Fig. 1).

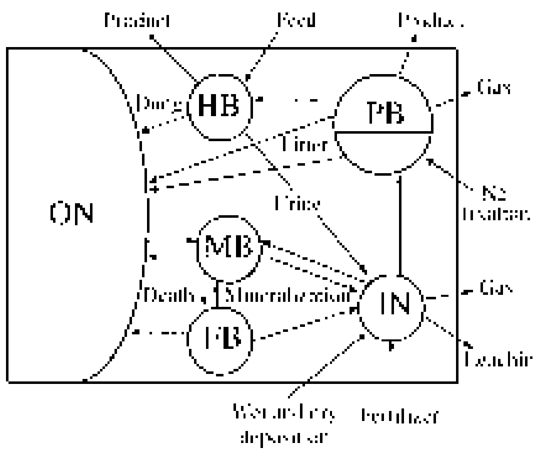

Figure 1. Schematic diagram of the N cycle in a typical pasture (Russelle 1992). Nitrogen pools are shown in their relative average sizes: ON, organic soil N (about 100 times larger than other pools, and which includes plant and animal residues); MB, soil microbial biomass N (bacteria, fungi, etc.); FB, soil mesofauna biomass N (earthworms, insects, etc.); IN, soil inorganic N (NH_4, NO_2, and NO_3); PB, plant biomass N (shoots and roots of living plants); and HB, large herbivore biomass N (livestock). The rectangle represents field boundaries. For clarity, not all directions of flux are shown.

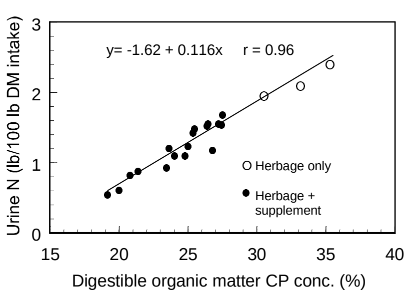

Figure 2. The relationship between N concentration in ingested feed (based on the digestible organic matter of the diet) and N excretion in urine of lactating dairy cows fed freshly cut, highly fertilized herbage or herbage plus different dietary supplements (redrawn from Valk and Hobbelink 1992). Nitrogen use efficiency for milk production increased from about 18 to about 28% and urine-N excretion decreased by 50% when low-protein, high energy supplements were fed.

Large amounts of N cycle through soil microorganisms and mesofauna, pasture plants, livestock, and soil organic matter (OM). The annual flux of N through biomass is larger than the total N removed in milk, meat, and wool (Brookes et al. 1985). Net N mineralization from soil OM in 12-yr-old swards ranged from 5 to 9% of the total soil N (Hatch et al. 1991), considerably higher than the 2% typical of annual cropping systems (Schepers and Mosier 1991).

Much of the uneaten herbage on living plants decomposes in pastures, as do dead roots on living plants and residues from plants that have died. Nitrogen cycling from these tissues is regulated in part by their C:N ratio, so species with high C:N ratios in root and shoot litter (e.g. low and moderately fertilized nonlegumes) will likely decrease N mineralization rates, whereas species with low C:N ratios (e.g., legumes and highly fertilized nonlegumes) will increase N mineralization (Gill et al. 1995, Wedin 1996). Soil OM under perennial ryegrass (*Lolium perenne* L.)/white clover (*Trifolium repens* L.) mixtures appears to be mineralized more rapidly than under grass alone.

Animal Excretion

Most of the feed N consumed by livestock is excreted. Lactating dairy cows, the most efficient converters of feed N to food N among the ruminants, excrete 70 to 80% of the N they consume (Yeck et al. 1975). In contrast, young growing animals excrete about 90% of feed N, and N excretion by mature animals essentially equals N consumption, except for wool or hair production (Worthington and Danks 1992). Furthermore, grazing herbivores harvest herbage from large areas and return most of the ingested N in excreta patches that cover 20% or less of the harvested area in a given year (O'Connor 1974).

Cattle urinate 8-12 times and defecate from 11-16 times per day (Haynes and Williams 1993). The size of excreta patches varies. For dairy cattle, average areas covered by urine range from 1.7 to 5.3 ft^2, whereas feces cover between 0.5 to 1.0 ft^2.

Variations in dietary N and energy content are reflected in urinary N output far more than in dung (Fig. 2; Whitehead 1970). Urine-N is "applied" by dairy cows at rates of about 1000 lb N/acre (Steele 1987) and in volumes equivalent to 100 inches per hour, greatly exceeding water infiltration capacity of soils. Urea and ammonium (NH_4) are found primarily in the upper 8 inches of soil in a urine spot, but deeper movement is detected occasionally (Williams and Haynes 1994). In well developed pasture soils, numerous macropores from old root channels, earthworms, and other faunal activity provide a means for rapid movement of ponded urine into the soil. Nitrification is delayed in urine spots due to the high pH, ammonia (NH_3) concentration, and osmotic strength of urine, and it may require more than a week before appreciable amounts of NO_3

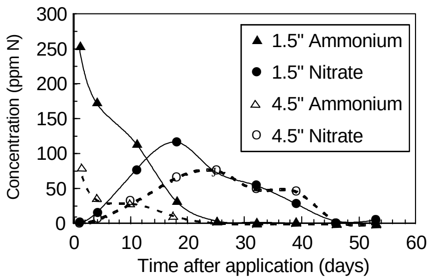

Figure 3. Time course of soil NH_4-N and NO_3-N concentrations in an artificial urine spot applied at 535 lb N/acre equivalent in midsummer (adapted from Ball et al. 1979). Two depth increments are shown, 0 to 3 inches (1.5" midpoint) and 3 to 6 inches (4.5" midpoint). Conversion of NH_4 to NO_3 is slower under low temperatures (e.g., in spring and autumn) than in midsummer.

"... significant amounts of fixed N can be transferred from legumes to grasses ..."

appear in a urine patch (Fig. 3; Monaghan and Barraclough 1992).

Dairy cows tend to excrete about 0.8 lb N in dung per 100 lb dry matter consumed, regardless of feed N concentration (Barrow 1987; Lantinga et al. 1987). Typical application rates in a dung patch are equivalent to about 900 lb N/acre for cattle (Haynes and Williams 1993). Little dung N is available to plants immediately, and subsequent N mineralization is regulated largely by air temperatures, precipitation, and insect activity.

N uptake and N_2 Fixation

Growing plants recover relatively small proportions of the urine-N, due to N losses and to N immobilization by soil microorganisms (Nannipieri et al. 1990). Recovery of urine-N often is in the range of 20 to 30% for highly productive pastures (Haynes and Williams 1993). Plant N recovery is better for urine deposited in spring and summer than in autumn, because of rapid plant growth. Plant species may differ in urine-N recovery, due both to inherent uptake ability and to adverse reactions to urine (scorch).

White clover in clover/grass pastures often shows annual N_2 fixation rates of 100 to 300 lb N/acre (Hoglund and Brock 1987). For different legumes and growing conditions, the amount of N_2 fixed ranges from about 1 to 4 lb N/acre/year for each 1% of legume in the mixture (Heichel and Henjum 1991).

Symbiotic N_2 fixation by legumes is reduced in urine spots. Averaged over four perennial forage legumes growing on an irrigated loamy sand soil in Minnesota, the amount of N derived from N_2 fixation was 87% for control plots, 75% for plots receiving dairy cow dung, and 26% for plots receiving dairy cow urine (Russelle and Buzicky 1988).

Legumes that are actively fixing atmospheric N_2 may not absorb as much NO_3 as grasses or legumes that are not fixing N_2 (Blumenthal and Russelle 1996). Moreover, significant amounts of fixed N can be transferred from legumes to grasses (Heichel and Henjum 1991). When clover comprises a large part (i.e. more than 30%) of a perennial ryegrass/white clover pasture, there may be little benefit in herbage, meat, or milk production with N fertilizer applications (Snaydon 1987). Thus, of all agricultural systems, perhaps pastures and mechanically harvested grasslands provide the greatest opportunity for legumes to make substantial contributions of N (Peterson and Russelle 1991).

N Losses

Surface Runoff

Water infiltration rates are faster and aggregate stability is higher under perennial forages than under annual cropping, so losses of N in sediment and in solution are lower for grasslands, except where livestock have damaged the plant cover or soil structure (Pearson and Ison 1987). In Ohio, less than 25% (9 lb N/acre) of the total N losses measured in leaching and runoff occurred via runoff from alfalfa (*Medicago sativa* L.)/grass mixtures (Owens et al. 1994).

Ammonia Volatilization

Volatilization of NH_3 is most rapid for the first 2 days after urine application and losses often total 15 to 25% of urine N (Haynes and Williams 1993). Greater losses may occur under the warm, dry conditions typical of summer in the USA, because NH_3 loss increases with temperature (Lockyer and Whitehead 1990). An estimated 0.77 million lb of NH_3-N are lost to the atmosphere each year from sheep production in the eastern USA (east of about 95° W latitude; Russelle 1996). The meat sold from these lambs contains about 1.2 million lb of N and sheared wool contains 0.5 million lb of N. Thus, NH_3 losses from sheep grazing in the eastern USA may equal 40% of the total N removed in economic products.

Ammonia losses from dung generally are smaller than from urine, primarily because little free NH_3 is present in feces (Kirchmann and Witter 1992). During the first 2 weeks after deposition, NH_3 losses were only 1 to 5% for cattle dung (Ryden et al. 1987). Ammonia can be absorbed by N-deficient herbage (Lemon and van Houtte 1980), thereby recycling it rapidly. Swards of perennial ryegrass or alfalfa absorbed up to 0.22 lb

"Denitrification is higher under grazing than with mechanical harvesting ..."

"... Deeply rooted pasture species can help attenuate NO_3 leaching losses."

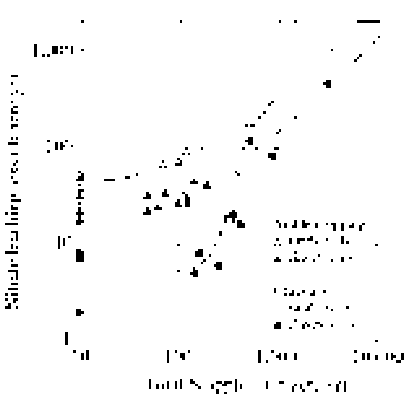

Figure 4. Relationship between fertilizer N rate and NO_3-N leaching losses for arable and grassland crops grown on sandy and clayey soils, adjusted to 1 acre-foot of drainage per year (redrawn from Kollenbrander 1981). Applied N was expressed as inorganic N for fertilizer and total N for manure.

N/acre/day (Bussink 1994).

Denitrification

Denitrification occurs when a combination of factors are present: a readily available supply of oxidizable sources of carbon, high concentrations of NO_3 or NO_2, and low availability of oxygen (Firestone and Davidson 1989). These conditions occur frequently under dung pats or in urine patches. The end products of denitrification are mainly N_2O and N_2. Nitrous oxide degrades atmospheric ozone and acts as a "greenhouse" gas by absorbing longwave radiation, whereas N_2 is benign.

Denitrification is higher under grazing than with mechanical harvesting (Ryden 1986). Lower rates of denitrification were found for perennial ryegrass/white clover swards than for fertilized perennial ryegrass. Urine spots on 10 to 15% of the pasture made a larger contribution to total denitrification loss in grazed perennial ryegrass/white clover than the rest of the pasture area (Ruz-Jerez et al. 1994). Rates of denitrification are higher in autumn, when NO_3 uptake by plants is slower and soil temperatures are not yet too cold to inhibit microbial activity (Ryden 1986), and may be large during spring thaw (Goodroad and Keeney 1984).

Nitrate Leaching

Another pathway of N loss is through NO_3 leaching. Although NO_3 leaching losses are generally smaller under perennial grasslands than under annual crops (Fig. 4), soil solution concentrations exceeding 50 ppm NO_3-N have been reported in grazed paddocks (MacDuff et al. 1990), much in excess of the Public Health limit of 10 ppm NO_3-N for drinking water in the USA. Leaching losses averaged about 75 lb N/acre/year under perennial ryegrass/white clover pastures that did not receive N fertilizer (Field et al. 1985). Scholefield and Tyson (1992) concluded that NO_3 losses are related more to rates of animal production than to composition of the pasture plant community.

Nevertheless, plant species vary in their ability to absorb inorganic N and in use of subsoil water supplies. In New Zealand, there was no appreciable NO_3 uptake below 18 inches by perennial ryegrass/white clover pastures (Field et al. 1985). Deeply rooted pasture species can help attenuate NO_3 leaching losses. Reed canarygrass (*Phalaris arundinacea* L.) and alfalfa, for example, both produced roots that penetrated to 9 feet after 3 years in a dense clay loam soil and apparently removed large amounts of soil NO_3 (Russelle et al. 1993).

Fraser et al. (1994) found only small leaching losses of N (8% of the 450 lb N/acre equivalent applied) from urine applied to large drainage lysimeters, and attributed that to N uptake by the sward (43% of the applied N) and high denitrification (28% of the applied N). Urine had been applied before rapid plant growth in spring and the investigators kept the soil moist to promote leaching. About 88% of the urine N taken up by the sward was found in the perennial ryegrass, with the remainder in white clover. Thus, adding a grass to a pure legume pasture should improve N retention and reduce N losses.

Leaching losses are most probable during the period from autumn to spring (except in frozen soils), when pasture growth is slow and precipitation exceeds evapotranspiration. In a grazing experiment at Prairie du Sac, WI, on the clay loam soil, we fed lactating Holsteins different rates of supplement during 1994 and 1995. During the leaching period from autumn 1994 to spring 1995 after one year of intensive rotational grazing, we measured leaching losses ranging from only 0 to 5 lb N/acre under the grazed pastures and adjacent mowed swards, but 19 lb N/acre directly under urine spots. There was high variability among drainage lysimeters within each paddock; about 80% of the lysimeters showed losses of less than 0.5 lb N/acre.

We were somewhat surprised at these low leaching losses, because soil NO_3-N concentrations in November 1994 averaged 37 lb N/acre more under pasture than under mowing, and averaged 275 lb N/acre higher directly under urine spots than under mowed swards. We suspect that denitrification may be substantial in this heavy-textured soil and that the pasture plants recovered some

"Changes in agricultural management will alter N storage and removal from soil OM, as well as affecting overall N cycling and loss."

"... set stocking caused higher NO_3 leaching, whereas rotational grazing caused higher gaseous losses."

of the subsoil NO_3 before it moved beneath the root zone. In addition, NO_3 measured in soil cores may not represent N available for leaching in highly structured, fine textured soils where most water moves through macropores and between soil aggregates.

N Balance

Changes in agricultural management will alter N storage and removal from soil OM, as well as affecting overall N cycling and loss. Intensified management of pastures in New Zealand leads to lower soil organic N concentrations (Field and Ball 1981). Declines over several years, despite N inputs through fertilization and N_2 fixation, imply that large losses occur in these systems under some combinations of soil and climate. However, on one soil series in South Australia, some pasture sites showed declining, whereas others showed increasing amounts of total N, all moving toward an apparently similar equilibrium level of 0.5% total N (Russell and Harvey 1959).

Recommendations for Minimizing N Losses

Although there is a greater propensity of terrestrial ecosystems to lose N as the intensity of production increases (O'Connor 1974, Ruz-Jerez et al. 1993), relatively efficient N use can be established in grazing systems because of rapid N recycling (Parsons et al. 1991), thereby limiting the need for high purchased inputs. For example, both greater N use efficiency and lower losses can be achieved in perennial ryegrass/white clover pastures than in heavily fertilized (375 lb N/acre/yr) perennial ryegrass pastures (Parsons et al. 1991), providing white clover populations do not exceed 90% of the stand (MacDuff et al. 1990).

Many management alternatives alter the pathways of N loss, but may not change the amount lost from the farm, if animal productivity or efficiency of N use in the animals does not change. For example, in comparing rotational grazing and set stocking of sheep in New Zealand with similar N inputs, Brock et al. (1990) found that animal productivity and N storage in the system were similar, but that set stocking caused higher NO_3 leaching, whereas rotational grazing caused higher gaseous losses. They concluded that graziers should select their management approach based on the susceptibility of water supplies to contamination.

N Fertilization

Fertilizer N rate and management obviously are important management tools to minimize environmental problems from all agricultural enterprises, including livestock farms using confinement systems, which tend to have excessive N inputs (Daberkow et al. 1988, Legg et al. 1989). Leaver (1991) found that on-farm N response in mown forage production averaged 20 lb DM/lb N applied, but was only 8 lb DM/lb N in grazed forages. Highly fertilized grass also contains surplus amounts of rumen degradable protein, which is lost by urination, than does grass grown with less fertilizer N (van Vuuren and Meijs 1987). Therefore, fertilizer N recommendations based on mown forages likely are excessive for grazed systems, particularly for intensive rotational grazing, and may result in environmental damage with little or no gain in animal productivity (Parsons et al. 1991).

Because most US states recommend less than 180 lb N/acre/year on pastures, N losses probably are small or moderate, in comparison to more intensive grazing systems practiced elsewhere (Brown 1996). It is commendable that some states recommend smaller fertilizer N rates on pasture than on mown forages. It is difficult enough to predict N needs accurately in relatively homogeneous systems like continuous corn production, so it may be impossible to accurately predict N needs for pastures (Snaydon 1987).

When clover comprises a significant part (i.e., more than 30%) of a perennial ryegrass/white clover pasture, there appears to be little benefit in herbage, meat, or milk production from N fertilizer applications (Snaydon 1987). Again, some US states recommend no N fertilizer on pastures with high proportions of

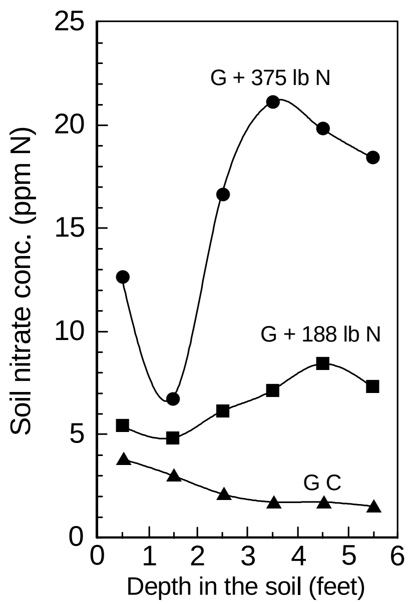

Figure 5. Soil NO_3-N concentration in late autumn beneath nonfertilized perennial ryegrass/white clover (GC) and fertilized (188 or 375 lb N/acre/year) perennial ryegrass (G) pastures grazed by sheep (redrawn from Parsons et al. 1991). Effective rooting depth of these forage species is limited to about 2 feet.

"Losses of 66% of the added N would occur through gaseous and solution pathways, whereas only 5% would be recovered in animal products."

legume in the stand. Snaydon (1987) suggested that two economic optima may exist — one with low or no N fertilizer applied to grass/legume swards, and one with high N fertilizer rates (270 to 350 lb N/acre/year) on pure grass swards. Evidence from the literature shows that the latter system is likely to cause significant environmental degradation (Fig. 5).

There will be less chance of having high soil NO_3 concentrations at times of high leaching if fertilization rate and timing match pasture plant needs. Rapid field tests for N supply may provide a means of reducing N applications while limiting concurrent reductions in productivity (Titchen and Scholefield 1992, Scholefield and Titchen 1995). Dutch researchers are developing and testing an approach that uses soil clay and OM content, depth to ground water, and weather to estimate fertilizer N needs of grassland (Oenema et al. 1992).

Over the long term, the computer simulation model of Scholefield et al. (1991) predicts that adding 360 lb N/acre to a previously nonfertilized grass/clover pasture grazed by beef cattle in England would result in a twofold increase in animal product, a threefold increase in NH_3 volatilization (up to 45 lb N/acre/year), 35 times more denitrification (up to 60 lb N/acre/year), and 33 times more NO_3 leaching (up to 150 lb N/acre/year). Soil organic N would decline without fertilizer N additions, but increase with 360 lb N/acre/year. Losses of 66% of the added N would occur through gaseous and solution pathways, whereas only 5% would be recovered in animal products. These predictions of N flux clearly will vary with climate, soils, plant communities, and herbivore species.

Feeding Management

Reducing the concentration of N in urine patches may be possible. Adding 2% molasses to drinking water increased water intake by grazing yearling steers, and reduced N concentration in urine from 8600 to 3700 ppm (Lantinga et al. 1987). No differences were observed when this experiment was repeated with lactating dairy cows, but addition of a readily degradable energy source to the water supply also may improve N use efficiency in milk and meat production. An alternative, albeit speculative, approach would be to identify pasture plant species that have diuretic properties, thereby increasing the frequency of urination and decreasing the total amount of N applied in each urine spot. It would be important to evaluate how this strategy might influence animal health and longevity.

Pasture herbage typically is high in rumen-degradable protein, but low in digestible energy, so moderate feeding of supplemental energy sources (corn silage, corn grain, etc.) that contain little protein may increase animal productivity and reduce N excretion (Weissbach 1994). Purchased supplemental feed comprises a substantial input of N on US dairy farms (Bacon et al. 1990). It is possible to improve N use efficiency and production in livestock by properly balancing digestible energy and protein in the diet (see chapter by L.D. Satter in this volume).

In addition, supplementation may reduce pasture consumption, thereby bringing protein consumption more in line with dietary needs (van Vuuren and Meijs 1987). If pasture consumption per animal declines, then more animals could be grazed on the pasture, resulting in higher profits per unit land area, and perhaps improving pasture fertility through improved excreta distribution. Hammond et al. (1993) showed that blood urea N concentrations may provide a potential tool to indicate when grazing livestock would respond to energy supplementation.

Grazing Time

Shortening the time grazing is allowed reduces direct deposition of excreta in the pastures, but this would require more mechanical harvesting and manure handling. In the Netherlands, many livestock are grazed during the day and are fed corn silage indoors at night to reduce both deposition of excreta in pasture and total dietary N concentration (Kuipers 1994). This approach likely would increase total NH_3 losses from the farm, unless stored manure is covered, but should reduce NO_3 leaching losses con-

"Draining wet soils may lead to vastly increased NO_3-N losses through tile lines ..."

"The multiple benefits of intensive rotational grazing, including economic returns, higher quality of life for the farm family, improved herd health, and more diverse farm ecosystems, are strong incentives to expand use of this management system."

siderably (Mandersloot et al. 1993). An additional approach is to remove pasture growth by mechanical means in the autumn, to avoid deposition of excreta before the autumn and spring leaching period ('t Mannetje and Paoletti 1992). Many graziers are considering keeping their animals outside year round. This practice may lead to increased surface water contamination on sloping soils that freeze during winter, just as occurs when slurry is applied to frozen soils.

Potential problems with higher grazing intensities include pasture damage by hoof traffic due to high animal numbers, especially in spring. Soil compaction can increase denitrification losses markedly, so avoidance of grazing on wet soil where hoof traffic will damage soil structure may reduce N loss by this pathway (Rheinbaben 1990). Draining wet soils may lead to vastly increased NO_3-N losses through tile lines (Scholefield et al. 1991), so decisions about artificial drainage should include consideration of potential surface and ground water quality impacts.

Caveats and Outlook

Caveats to these recommendations are that measurements of N cycling in the USA are rare, and data from other areas of the world may not apply to many of our conditions. Projection of effects on N cycling arising from these differences is difficult, at best, because of the dynamic, interacting nature of these factors. Despite these reservations, many of these recommendations should help decrease N losses and improve the recycling of N in our pasture systems.

The multiple benefits of intensive rotational grazing, including economic returns, higher quality of life for the farm family, improved herd health, and more diverse farm ecosystems, are strong incentives to expand use of this management system. As graziers become more aware of how pasturing affects N cycling, we can expect that they will help develop and incorporate innovative ways to better manage their systems and prevent environmental degradation.

References

Bacon, S.C., L.E. Lanyon and R.M. Schlauder, Jr. 1990. Plant nutrient flow in the managed pathways of an intensive dairy farm. Agronomy Journal 82:755-761.

Ball, R., D.R. Keeney, P.W. Theobald and P. Nes. 1979. Nitrogen balance in urine-affected areas of a New Zealand pasture. Agronomy Journal 71:309-314.

Barrow, N.J. 1987. Return of nutrients by animals. In R.W. Snaydon, ed., Managed grasslands: Analytical studies, pp. 181-186. Elsevier, Amsterdam.

Blumenthal, J.M., and M.P. Russelle. 1996. Subsoil nitrate uptake and symbiotic dinitrogen fixation by alfalfa. Agronomy Journal 88: (In press).

Brock, J.L., P.R. Ball and R.A. Carran. 1990. Impacts of management on leaching of nitrate from pastures. Proceedings of the New Zealand Grassland Association 52:207-210.

Brookes, P.C., D.S. Powelson and D.S. Jenkinson. 1985. The microbial biomass in soil. In A.H. Fitter et al., eds., Ecological interactions in soil: Plants, microbes and animals, pp.123-125. Blackwell, Oxford, U.K.

Brown, J.R. 1996. Fertility management of harvested forages in the Northern States. In R.E. Joost and C.A. Roberts, eds., Nutrient cycling in forage systems. March 7-8, 1996, Columbia, MO, pp. 93-112. Potash and Phosphate Institute and the Foundation for Agronomic Research, Manhattan, KS.

Bussink, D.W. 1994. Relationships between ammonia volatilization and nitrogen fertilizer application rate, intake and excretion of herbage nitrogen by cattle on grazed swards. Fertilizer Research 38:111-121.

Daberkow, S., L. Hansen and H. Vroomen. 1988. Low input practices. In Outlook. pp. 22-25, Economic Research Service, USDA, Washington, D.C.

Field, T.R.O., and P.R. Ball. 1981. Nitrogen balance in an intensively utilised dairyfarm system. Proceedings of the New Zealand Grassland Association. 43:64-69.

Field, T.R.O., P.R. Ball and P.W. Theobald. 1985. Leaching of nitrate from sheep-grazed pastures. Proceedings of the New Zealand Grassland Association. 46:209-214.

Firestone, M.K., and E.A. Davidson. 1989. Microbiological basis of NO and N_2O production and consumption in soil. In M.O. Andreae and D.S. Schimel, eds., Exchange of trace gases between terrestrial ecosystems and the atmosphere. p. 7-21. John Wiley & Sons, Ltd.

Fraser, P.M., K.C. Cameron and R.R. Sherlock. 1994. Lysimeter study of the fate of nitrogen in animal urine returns to irrigated pasture. European Journal of Soil Science 45:439-447.

Gill, K., S.C. Jarvis and D.J. Hatch. 1995. Mineralization of nitrogen in long-term pasture soils: Effects of management. Plant and Soil 172:153-162.

Goodroad, L.L., and D.R. Keeney. 1984. Nitrous oxide emissions from soils during thawing. Canadian Journal of Soil Science 64:187-194.

Hammond, A.C., W.E. Kunkle, D.B. Bates and L.E. Sollenberger. 1993. Use of blood urea nitrogen concentration to predict response to protein or energy supplementation in grazing cattle. In Proc. XVII International Grassland Congress, pp. 1989-1991.

Hatch, D.J., S.C. Jarvis and S.E. Reynolds. 1991. An assessment of the contribution of net mineralization to N cycling in grass swards using a field incubation method. Plant and Soil 138:23-32.

Haynes, R.J., and P.H. Williams. 1993. Nutrient cycling and soil fertility in the grazed pasture ecosystem. Advances in Agronomy 49:119-199.

Heichel, G.H., and K.I. Henjum. 1991. Dinitrogen fixation, nitrogen transfer, and productivity of forage legume-grass communities. Crop Science 31:202-208.

Hoglund, J.H., and J.L. Brock. 1987. Nitrogen fixation in managed grasslands. In R.W. Snaydon, ed., Managed grasslands: Analytical studies, pp. 187-196. Elsevier, Amsterdam.

Kirchmann, H. and E. Witter. 1992. Composition of fresh, aerobic and anaerobic farm animal dungs. Bioresource Technology 40:137-142.

Kollenbrander, G.J. 1981. Leaching of nitrogen in agriculture. In J.C. Brogan, ed., Nitrogen losses and surface run-off, pp.199-216. Nijhoff/Junk, Dordrecht, The Netherlands.

Kuipers, A. 1994. Nutrient flow and management practices on farm level: The Netherlands. In Nutrient management, manure and the dairy industry: European perspectives and Wisconsin's challenges, Babcock Institute Technical Workshop. Aug. 31-Sept. 2, 1994, pp. 23-27. University of Wisconsin, Madison, WI.

Lantinga, E.A., J.A. Keuning, J. Groenwold and P.J.A.G. Deenen. 1987. Distribution of excreted nitrogen by grazing cattle and its effects on sward quality, herbage production and utilization. In H.G. van der Meer et al., eds., Animal manure on grassland and fodder crops. Fertilizer or Waste? pp. 103-117. Martinus Nijhoff, Dordrecht, The Netherlands.

Leaver, J.D. 1991. The role of fertiliser nitrogen in the 1990's. In C. S. Mayne, ed., Management issues for the grassland farmer in the 1990's, pp.140-147. British Grassland Society Occasional Symposium No. 25. Maidenhead.

Legg, T.D., J.J. Fletcher and K.W. Easter. 1989. Nitrogen budgets and economic efficiency: A case study of southeastern Minnesota. Journal of Production Agriculture 2:110-116.

Lemon, E. and R. van Houtte. 1980. Ammonia exchange at the land surface. Agronomy Journal 72:876-883.

Lockyer, D.R. and D.C. Whitehead. 1990. Volatilization of ammonia from cattle urine applied to grassland. Soil Biology and Biochemistry 22:1137-1142.

MacDuff, J.H., S.C. Jarvis and D.H. Roberts. 1990. Nitrate leaching under grazed grassland: Measurements using ceramic cup soil solution samplers. In R. Merckx, H. Vereecken and K. Vlassak, eds., Fertilization and the environment, pp. 72-78. Leuven University Press, Leuven, The Netherlands.

Mandersloot, I.F., A. van der Kamp and I.A.T.J. van Scheppingen. 1993. Farm economic consequences of reducing nitrogen losses on dairy farms.. In XXV CIOSTA CIGR V Congress, pp. 377-385.

'T Mannetje, L. and R. Paoletti. 1992. Grassland production and the environment. In Proceedings of the 14th General Meeting of the European Grassland Federation, Lahti, Finland, June 8-11, 1992, pp. 19-32. European Grassland Federation.

Monaghan, R.M. and D. Barraclough. 1992. Some chemical and physical factors affecting the rate and dynamics of nitrification in urine-affected soil. Plant and Soil 143:11-18.

Nannipieri, P., C. Ciardi, T. Palazzi and L. Badalocco. 1990. Short-term nitrogen reactions following the addition of urea to a grass-legume association. Soil Biology and Biochemistry 22:549-553.

O'Connor, K.F. 1974. Nitrogen in agrobiosystems and its environmental significance. New Zealand Journal of Agricultural Science 8:137-148.

Oenema, O., F.A. Wopereis, G.H. Ruitenberg and D.W. Bussink. 1992. Towards efficient use of nitrogen on intensively managed grassland in The Netherlands. In Proceedings of the 14th General Meeting of the European Grassland Federation, Lahti, Finland, June 8-11, 1992, pp. 519-522. European Grassland Federation.

Owens, L.B., W.M. Edwards and R.W.V. Keuren. 1994. Groundwater nitrate levels under fertilized grass and grass-legume pastures. Journal of Environmental Quality 23:752-758.

Parsons, A.J., R.J. Orr, P.D. Penning and D.R. Lokyer. 1991. Uptake, cycling and fate of nitrogen in grass-clover swards continuously grazed by sheep. Journal of Agricultural Science (Cambridge) 116:47-61.

Pearson, C.J., and R.L. Ison. 1987. Agronomy of grassland systems. Cambridge University Press, Cambridge.

Peterson, T.A., and M.P. Russelle. 1991. Alfalfa and the nitrogen cycle in the Corn Belt. Journal of Soil and Water Conservation 46:229-235.

Rheinbaben, W. v. 1990. Nitrogen losses from agricultural soils through denitrification — a critical evaluation. Zeitschrift für Pflanzenernährung und Bodenkunde 153:157-166.

Russell, J.S. and D.L. Harvey. 1959. Changes in the nitrogen content and pH of the Mobilong clay as influenced by land use. Australian Journal of Agricultural Research 10:637-650.

Russelle, M.P. 1991. Nitrogen cycling in pasture and range. Journal of Production Agriculture 5:13-23.

Russelle, M.P. 1996. Nitrogen cycling in pasture systems. In R.E. Joost and C.A. Roberts, ed., Nutrient cycling in forage systems. March 7-8, 1996, Columbia, MO, pp.125-166. Potash and Phosphate Institute and Foundation for Agronomic Research, Manhattan, KS.

Russelle, M.P., and G.C. Buzicky. 1988. Legume response to fresh dairy cow excreta. In 1988 Forage and Grassland Conference, Baton Rouge, Louisiana, April 11-14, 1988, pp. 11-14. American Forage and Grassland Council.

Russelle, M.P., S.D. Evans and D.K. Barnes. 1993. Use of deeply rooted perennial forages for subsoil nitrate removal. In Agronomy Abstracts, Cincinnati, OH, Nov. 7-12, 1993, p. 117. American Society of Agronomy, Madison, WI.

Ruz-Jerez, B.E., R.E. White and P.R. Ball. 1993. Nitrogen dynamics in three contrasting grassland systems: implications for pasture productivity and the potential for environmental pollution. In Proc. XVII International Grassland Congress, pp.818-820.

Ruz-Jerez, B.E., R.E. White and P.R. Ball. 1994. Long-term measurement of denitrification in three contrasting pastures grazed by sheep. Soil Biology and Biochemistry 26:29-39.

Ryden, J.C. 1986. Gaseous losses of nitrogen from grassland. In H.G. van der Meer, J.C. Ryden and G.C. Ennik, eds., Nitrogen fluxes in intensive grassland systems, p. 59-73. Martinus Nijhoff, Dordrecht, The Netherlands.

Ryden, J.C., D.C. Whitehead, D.R. Lockyer, R.B. Thompson, J.H. Skinner and E.A. Garwood. 1987. Ammonia emission from grassland and livestock production systems in the UK. Environmental Pollution 48:173-184.

Schepers, J. S. and R. H. Fox. 1989. Estimation of N budgets for crops. In R. F. Follett, ed., Nitrogen management and ground water protection, pp. 221-246. Elsevier, Amsterdam.

Schepers, J.S., and A.R. Mosier. 1991. Accounting for nitrogen in nonequilibrium soil-crop systems. In R.F. Follett et al. (ed.) Managing nitrogen for groundwater quality and farm profitability, pp. 125-138. Soil Science Society of America, Madison, WI.

Scholefield, D., D.R. Lockyer, D.C. Whitehead and K.C. Tyson. 1991. A model to predict transformations and losses of nitrogen in UK pastures grazed by beef cattle. Plant and Soil 132:165-177.

Scholefield, D. and N.M. Titchen. 1995. Development of a rapid field test for soil mineral nitrogen and its application to grazed grassland. Soil Use Management 11:33-43.

cholefield, D. and K.C. Tyson. 1992. Comparing levels of nitrate leaching from grass/clover and N-fertilized grass swards grazed with beef cattle. In Proceedings of the 14th General Meeting of the European Grassland Federation. Lahti, Finland, June 8-11, 1993, pp. 530-533. European Grassland Federation.

Snaydon, R.W. 1987. Fertilizer inputs and botanical composition. In R.W. Snaydon, ed., Managed grasslands: Analytical studies, pp. 239-246. Elsevier, Amsterdam.

Steele, K.W. 1987. Nitrogen losses from managed grassland. In R.W. Snaydon, ed., Managed grasslands: Analytical studies, pp. 197-204. Elsevier, Amsterdam.

Titchen, N.M. and D. Scholefield. 1992. Strategy of fertilizer nitrogen applications to grassland. Aspects of Applied Biology 30:223-229.

Undersander, D., B. Albert, P. Porter, A. Crossley and N. Martin. 1993. Pastures for profit: A guide to rotational grazing. Cooperative Extension Publication, Madison, WI No. A3529.

Valk, H., and M.E.J. Hobbelink. 1992. Supplementation of grazing dairy cows to reduce enviromental pollution. In 14th General Meeting of the European Grassland Federation. Lahti, Finland. pp. 400-405. European Grassland Federation.

van Vuuren, A.M. and J.A.C. Meijs. 1987. Effects of herbage composition and supplement feeding in the excretion of nitrogen in dung and urine by grazing dairy cows. In H. G. van der Meer et al., eds., Animal manure on grassland and fodder crops. Fertilizer or waste? pp. 17-25. Martinus Nijhoff, Dordrecht.

Wedin, D. 1996. Nutrient cycling in grasslands: An ecologist's perspective. In R.E. Joost and C.A. Roberts, eds., Nutrient cycling in forage systems. March 7-8, 1996, Columbia, MO, pp. 29-44. Potash and Phosphate Institute and the Foundation for Agronomic Research, Manhattan, KS.

Weissbach, F. 1994. Nutrient budgets and farm management to reduce nutrient emissions: A German perspective. In Nutrient management, manure and the dairy industry: European perspectives and Wisconsin's challenges. Babcock Institute Technical Workshop. Aug. 31-Sept. 2, 1994, pp. 43-55. University of Wisconsin, Madison, WI.

Whitehead, D.C. 1970. The role of nitrogen in grassland productivity. Commonwealth Agricultural Bureau, Farnham Royal, Bucks, U.K. Bulletin No.48.

Williams, P.H. and R.J. Haynes. 1994. Comparison of initial wetting pattern, nutrient concentrations in soil solution and the fate of ^{15}N-labelled urine in sheep and cattle urine patch areas of pasture soil. Plant and Soil 162:49-59.

Worthington, T.R. and P.W. Danks. 1992. Nitrate leaching and intensive outdoor pig production. Soil Use and Management 8:56-60.

Yeck, R.G., L.W. Smith, and C.C. Calvert. 1975. Recovery of nutrients from animal wastes. An overview of existing options and potentials for use in feed. In Proceedings of the 3rd International Symposium on Livestock Wastes, Urbana-Champaign, IL. April 21-24, 1975, pp. 193-194. American Society of Agricultural Engineers, St. Joseph, MI.