Feed and manure use in low-N-input and high-N-input dairy cattle production systems

J Mark Powell

USDA-Agricultural Research Service, US Dairy Forage Research Center, Madison, Wisconsin, USA

E-mail: mark.powell@ars.usda.gov

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Abstract

In most parts of Sub-Saharan Africa fertilizers and feeds are costly, not readily available and used sparingly in agricultural production. In many parts of Western Europe, North America, and Oceania fertilizers and feeds are relatively inexpensive, readily available and used abundantly to maximize profitable agricultural production. A case study, dairy systems approach was used to illustrate how differences in feed and manure management in a low-N-input dairy cattle system (Niger, West Africa) and a high-N-input dairy production system (Wisconsin, USA) impact agricultural production and environmental N loss. In Niger, an additional daily feed N intake of 114 g per dairy animal unit (AU, 1000 kg live weight) could increase annual milk production from 560 to 1320 kg AU\(^{-1}\), and the additional manure N could greatly increase millet production. In Wisconsin, reductions in daily feed N intake of 100 g AU\(^{-1}\) would not greatly impact milk production but decrease urinary N excretion by 25% and ammonia and nitrous oxide emissions from manure by 18% to 30%. In Niger, compared to the practice of housing livestock and applying dung only onto fields, corralling cattle or sheep on cropland (to capture urinary N) increased millet yields by 25% to 95%. The additional millet grain due to dung applications or corralling would satisfy the annual food grain requirements of 2–5 persons; the additional forage would provide 120–300 more days of feed for a typical head of cattle; and 850 to 1600 kg ha\(^{-1}\) more biomass would be available for soil conservation. In Wisconsin, compared to application of barn manure only, corralling heifers in fields increased forage production by only 8% to 11%. The application of barn manure or corralling increased forage production by 20% to 70%. This additional forage would provide 350–580 more days of feed for a typical dairy heifer. Study results demonstrate how different approaches to feed and manure management in low-N-input and high-N-input dairy cattle systems impact milk production, manure N excretion, manure N capture, N recycling and environmental N loss.

Keywords: dairy, nitrogen, Africa, USA

1. Introduction

Agricultural production is a function of bio-physical processes that transform solar energy, water, and nutrients into food, feed and other products. Nitrogen (N) is the most limiting nutrient for productive agriculture. Crops and livestock are limited however in their abilities to incorporate N into products. For example, after application to soil a general range of 25% to 50% of the N contained in land-applied fertilizers and animal manures may be taken up by annual crops and pastures. Feed N use efficiencies, or the relative amount of feed N consumed by livestock incorporated into products (e.g., meat, milk, eggs) ranges from approximately 10% to 40% (Van der Hoek 1998, Flachowsky 2002). Improving N use efficiencies has been identified as a key component to productive, profitable and environmentally-sound agriculture (Flachowsky and Lebzien 2006, Sutton et al 2013).

Nitrogen impacts on agricultural production and the environment depend largely on levels of N applied. In Sub-
Saharan Africa (SSA) fertilizers and feeds are costly, not readily available and therefore used sparingly. Over the past 25 years or so there has been increasing evidence and concern that soils in SSA are being mined of their nutrients (Stoorvogel and Smaling 1990, Sanchez 2002, Henao and Baanante 2006), which jeopardizes the long-term sustainability of these low-N-input agricultural systems. In many parts of Western Europe, North America, and Oceania (WENAO), fertilizers and feeds are relatively inexpensive, readily available and used abundantly in the pursuit of profitable agricultural production. Over the past 25 years or so clear evidence has emerged that many high-N-input agricultural systems incur high N loss, which impairs water and air quality at local, regional and global scales (Rouse et al 1999, Gallaway et al 2003, 2008, Erisman et al 2007).

A major part of the global agricultural N cycle takes place within livestock production systems. For example on most dairy farms in WENAO, fertilizers, manure and other N inputs are used to grow forages, grains and other feeds, which are fed to cows as fresh or stored feeds, and a portion of the N excreted in manure is land-applied with fertilizers and atmospherically-fixed-N by legumes in rotations to produce more feed. Feed N intake and the balance between feed N and energy are principal factors that impact feed N use efficiency and milk production. An over consumption of feed N leads to increases in urea N excretion in urine, most of which is lost as ammonia during manure collection, storage and land application. Urea is hydrolyzed, nitrified and denitrified in soil and lost as nitrate and nitrous oxide, the most potent greenhouse gas emitted from agriculture (de Klein, Eckard 2008).

Before the advent of chemical fertilizer, dairy farmers sought to maximize the capture and recycling of manure nutrients through crops and pasture. In crop-livestock systems of SSA where fertilizers are costly and not widely available, manure is a precious soil fertility amendment (Powell et al 1995, Murwira et al 1995, Harris 2002). Under current management practices on confinement dairy farms (cows fed conserved feeds in barns) in WENAO, much energy and labor is utilized to collect, haul and land apply dairy manure, and during these practices most urinary N is lost as ammonia. To highlight the synergistic nature of N use in agricultural systems and to contrast N use outcomes, the objective of this study was to demonstrate how feed management impacts milk and manure production, and how dairy herd management impacts the capture and recycling of manure N through croplands in low-N-input (SSA) and high-N-input (WEANO) dairy cattle systems.

2. Methods

Information on dairy herd composition, feed dry matter intake (DMI), nitrogen intake (NI), and manure N excretion (Nex) was obtained from a data set used recently to determine feed-milk-manure N relationships for the global dairy herd (Powell et al 2013). The data sub-set used in the present study included information for 37 countries in SSA and 40 countries in WENAO. This information was used to highlight differences in dairy herd composition, milk production, feed N use efficiency (percentage of NI secreted as milk N; NUE-milk) and Nex in these contrasting N use environments (table 1).

Data from two field experiments were analyzed to illustrate relationships between dairy cattle management, the amount and form of Nex applied to cropland, and subsequent impacts of manure on food, forage and crop residue production. The first experiment (Powell et al 1998) was conducted in Niger, West Africa to determine how cattle and sheep management impacts dung N (DN) and urinary N (UN) applications to fields and yields of pearl millet (Pennisetum glaucum (L.) R.Br.). This study was part of other investigations that sought to maximize manure N capture and use in these low-N-input productions systems. The second study (Powell and Russell 2009) was conducted in Wisconsin USA which investigated how dairy heifer management impacted DN and UN applications to fields and yields of a crop rotation that included wheat (Triticum spp L.), sudangrass (Sorghum X drumondii), winter rye (Secale cereale L.) and corn (Zea mays L.). This experiment sought to develop management practices that would reduce environmental N loss from outside cattle holding areas (Powell et al 2005) in this high-N-input dairy production system.

2.1. Manure trial in Niger, West Africa

A four-year field trail was conducted on a sandy, siliceous, isohyperthermic Psammentic Paleustalf (West et al 1984) at the International Crops Research Institute for the semi-arid tropics (ICRISAT) Sahelian Centre (ISC); 13°15′N, 2°18′E in the Republic of Niger, West Africa. Average annual rainfall at ISC is approximately 560 mm of which 95% falls during the May–September cropping season. Experimental treatments included a factorial combination of cattle or sheep dung only applications, the equivalent of one, two or three nights of dung production with or without urine, every one, two or three years. There were six replicates per treatment arranged in a completely randomized block design. During each study year, dung was applied during the two- to three-month dry period just prior to the rainy season and the planting of millet. Cattle and sheep were herded together on natural pasture for 10 h to 14 h daily. At night, the herd was split with half the cattle or sheep put into portable corrals centered over fields and yields of a field trial was conducted on a sandy, siliceous, isohyperthermic Psammentic Paleustalf (West et al 1984) at the International Crops Research Institute for the semi-arid tropics (ICRISAT) Sahelian Centre (ISC); 13°15′N, 2°18′E in the Republic of Niger, West Africa. Average annual rainfall at ISC is approximately 560 mm of which 95% falls during the May–September cropping season. Experimental treatments included a factorial combination of cattle or sheep dung only applications, the equivalent of one, two or three nights of dung production with or without urine, every one, two or three years. There were six replicates per treatment arranged in a completely randomized block design. During each study year, dung was applied during the two- to three-month dry period just prior to the rainy season and the planting of millet. Cattle and sheep were herded together on natural pasture for 10 h to 14 h daily. At night, the herd was split with half the cattle or sheep put into portable corrals centered over field plots (dung plus urine) for the designated number of nights (figures 1(a) and (b)). The remainder of the herd spent their nights in nearby stalls, and dung was collected each morning and spread on the ‘dung only’ plots. More detailed information on experimental design and statistical analyses, and the management of cattle, sheep, manure and millet yields can be found in Powell et al (1998).

2.2. Manure trial in Wisconsin, USA

A four-year field trial was conducted on a fine-silty, mixed, superactive, mesic Typic Agriudoll (USDA-NRCS 2004) at the research farm of US Dairy Forage Research Center in Wisconsin USA; 43°19′N, 89°44′W. Average annual rainfall
is approximately 790 mm of which 75% falls during the April–October cropping season. Two manure application methods were evaluated, each at two application levels: (1) the conventional method of keeping dairy heifers in a barn and the manure (dung plus small amounts of urine) produced during two (B2) or four (B4) days was scraped from barn floors and hauled to fields; and (2) the coralling method involved putting heifers in fields for two (C2) or four (C4) days to apply all dung and urine directly on soil (figures 1(c) and (d)). Twenty manure application periods (months) occurred during four seasons over a two year period. There were three replicates per treatment arranged in a completely randomized block design for each of the four seasons. Each manure application season was followed by a three-year crop rotation. A rotation of wheat-sudangrass-winter rye-corn-winter rye-corn was grown on plots that received manure during the two spring-summer seasons, and a rotation of corn-winter rye-corn-winter rye-corn was grown on plots that received manure during the two fall-winter seasons. More detailed information on experimental design and statistical analyses, and the management of heifers, feed, manure and crop yields can be found in Powell and Russelle (2009).

2.3. Manure management impacts on crop production

For both the Niger and Wisconsin experiments, two methods were used to evaluate impacts of manure collection and land
application methods on crop production. To evaluate urine effects, yields in the corralled plot (dung plus urine) were divided by yields in dung only plot (or dung plus some urine in Wisconsin). To evaluate overall manure treatment (dung, with or without urine) effects, yields in control plots (no manure applications) were subtracted from yields in each manure treatment plot.

In Niger, millet grain yields were determined in each plot each year. This was designated as the food component of total millet dry matter (DM) production. Millet grain production (kg ha$^{-1}$) was divided by 165.5 kg, the annual per capita millet grain consumption in Niger during the period of the experiment (FAO and ICRISAT 1996). The quotient was the number of additional adults per hectare per year that the increase in millet grain due to manure applications would feed. Grain was subtracted from total millet DM and the remaining millet stover (the millet biomass that remains after grain harvest) was divided into two components: (1) forage DM consisting of chaff, immature panicles, upper stover (leaves plus stalks) and tillers, and, (2) biomass designated for soil conservation consisting of middle and lower stover portions (Powell and Fussell 1993). The number of cattle feed days obtained from the additional millet forage production due to manure applications was calculated by dividing forage DM by a daily forage intake requirement of 6.5 kg cattle$^{-1}$ (one cattle having 320 kg live weight consuming 2.0% of bodyweight in the form of millet stover, Powell et al 2013).

In Wisconsin, only total above-ground crop DM production was recorded in each treatment plot over the three-year rotation that followed manure applications. All crop DM in the rotations was designated as forage that could be used to feed dairy heifers. The number of heifer feed days obtained from the additional forage DM due to manure applications was calculated by dividing total forage DM by an assumed daily DMI of 9.5 kg heifer$^{-1}$ (one heifer having 450 kg live weight and consuming 2.1% of bodyweight, Hoffman and Kester 2013).

3. Results and discussion

3.1. Herd composition, feed nitrogen, milk production and manure nitrogen excretion

Dairy cattle herd compositions in SSA and WENAO differ considerably (table 1). Of the total animal units (one AU = 1000 kg animal live weight), 56% in SSA and 79% in WENAO are adult or replacement female animals. In SSA, lactating cows are much smaller and become pregnant much later and less often than adult females in WENAO. The feed DMI and NI of cattle in SSA are 85% and 60% of feed DMI and NI of dairy cows in WENAO, yet median milk production in SSA is only 10% of median milk production in WENAO. The amount of NI secreted as milk N (NUE-milk) is also 5 to 6 times lower in SSA than WENAO. The recent global analysis (Powell et al 2013) revealed great regional differences in distribution of dairy cattle in classes of NUE-milk. For the present analysis, the partitioning of all lactating cows into NUE-milk classes of <10%, <20% and <25% for SSA is 92%, 98% and 100% and for WENAO is 0%, 3% and 69%, respectively. As NUE-milk within the range of 20% to 35% are possible on commercial dairy farms (Flachowsky 2002, Flachowsky and Lebzien 2006, Chase 2003), these results indicate that substantial improvements in NUE-milk seem possible for both regions, especially SSA.

Because of low milk production and low NUE-milk, Nex per unit of milk is 7–8 times greater in SSA than in WENAO. The high proportion of non-lactating cows, the great variability and very low levels of milk production and NUE-milk in SSA reflect the multiple uses of cattle, the least which may be commercial milk production. Although commercial milk production is important in many peri-urban areas, in the mostly rural areas of SSA cattle are kept for milk, meat and many other purposes, such as social status, wealth store, and manure which is used for fuel, construction and as a precious soil fertility amendment. There appears to be a great need to better differentiate between dairy, beef and multi-purpose cattle production systems when making global assessments of environmental impacts of milk production (Powell et al 2013).

The provision of additional feed N to dairy cattle (as part of N-energy balanced rations) would seemingly be used much more efficiently in SSA than in WENAO (figure 2). The slope (3.2 g milk N per 100 g of feed N for each increase of 1000 kg milk AU$^{-1}$) of the linear regression for lactating cows in SSA is four times greater than the slope (0.8 g milk N per 100 g of feed N for each increase of 1000 kg milk AU$^{-1}$) of the linear regression for the higher production cows in WENAO. The increases in NUE-milk associated with increases in milk production are also more predictable in SSA (R$^2$=0.98) compared to WENAO (R$^2$=0.66). There are many interrelated factors however that affect relationships between NI, milk production and NUE-milk that are beyond the scope of
the present analysis. For example, animal breed, reproductive performance and health, and perhaps most importantly the balancing of feed N with digestible energy, amino acids, and minerals in rations fed to dairy cattle have great impacts on milk production and NUE-milk (Chase 2003, Broderick 2003, Flachowsky and Lebzien 2006, Powell et al. 2014).

3.2. Manure impacts on crop production and uses

The recent life cycle assessment (LCA) of the global dairy herd revealed that knowledge of feed N intake and milk production allow for accurate calculations of NUE-milk, Nex and the relative amounts of Nex in dung and urine (Powell et al. 2013). In Niger average annual milk production is 560 kg AU−1, NUE-milk is 2.8%, and Nex is 223 g N per kg of milk. In the USA annual milk production is 11 900 kg AU−1, NUE-milk is 25.0%, and the amount of Nex is 14 g N per kg of milk. How dairy cattle are managed impacts the amount of dung N and urinary N captured and recycled through cropping systems and environmental N loss.

In Niger, corralling cattle (or sheep) on cropland overnight between cropping periods to apply both dung and urine (figures 1(a) and (b)) increased millet total DM by averages of 25% to 95% compared to the practice of housing the livestock overnight and applying only collected dung onto fields (figure 3). Whereas for cattle the greatest percentage yield increase (95%) was associated with corralling every year, for sheep similar yield increases (60% to 80%) were obtained by corralling every year or every 2nd year.

The positive effects of UN on millet may be attributed not only to additional N but also the ability of UN to increase in soil pH and plant availability of phosphorus (P) in these sandy, P deficient soils (Powell et al. 1998). In Niger the residual effects of UN (as measured in the every 2nd and every 3rd year plots, figure 3) were much greater than expected. Residual N availability may have been due to numerous factors, such as a greater than anticipated immobilization of applied N by the soil microbial pool, and the sequestration of N in soil minerals, which became available during subsequent years.

In Wisconsin, the effects of corralling (figures 1(c) and (d)) on crop yields were much less dramatic than what was observed in Niger (figure 3). Corrauling dairy heifers on cropland for 2 or 4 days increased total forage DM yield by only 8%–11%, compared to the practice of housing heifers and applying only the manure scrapped from barn floors. The principal reasons for these low responses were likely associated with (1) the collection and application of some urine in the ‘barn manure’ plots, (2) overall manure N applications were 4–5 times greater than agronomic N requirements, and (3) the high fertility of loam soils in Wisconsin compared to the sandy soils of Niger. Related to the second point, an objective of the Wisconsin study was to determine manure N availability to crops in outside cattle holding areas (figure 1(c)) where 120–850 kg ha−1 of manure N is deposited annually and unmanaged (Powell et al. 2005). Related to the third point, at the experimental site approximately 115 kg N ha−1 is mineralized from this silt loam soil annually, which makes determination of manure N effects on crop yields and crop N uptake difficult to detect (Powell et al. 2011a).

Overall results of the Niger and Wisconsin experiments demonstrate the importance of herd and manure management on UN capture, recycling Nex through crops, especially in low-N-input dairy production systems. Although direct measurements of N loss were not made, partial N balances revealed substantial N loss likely occurred in both environments. In Niger, it was estimated that approximately 30% to 50% of UN deposited in corrals was lost as ammonia (Powell et al. 1998). In Wisconsin, 20% to 30% of UN was estimated to have been lost during manure collection and transport to fields. Although manure N recovery by crops (% of Nex) was 30% to 50% higher in areas where dairy heifers had been corralled compared to application of barn manure, from 50% to 70% of the Nex deposited in corral plots could not be accounted for indicating large N loss (Powell and Russell 2009).

As mentioned previously, the provision of more feed N to dairy cattle in SSA would not only likely be used efficiently to produce more milk (figure 2) but would also increase Nex, which could increase overall agricultural production. For example in Niger, applications of cattle dung alone every 1, 2 or 3 years increased total millet DM by approximately 2000 kg ha−1 (figure 4(a)). The additional grain yield per hectare due to applications of cattle dung only would satisfy the annual millet grain requirements of approximately 2–3 persons; the additional forage per hectare would provide approximately 120–140 more feeding days for a typical head of cattle; and the remaining 840 kg of biomass per hectare could be used for soil conservation (which may also have long-term positive effects on soil fertility, crop and milk production). Millet yields were similar across the cattle dung application intervals of every 1, 2 or 3 years (figure 4(a)) indicating that most of dung’s positive impacts on millet yield occur during the growing season that immediately follows dung application.

Figure 3. Percent yield increases due to corralling in Niger (low-N-input environment) and Wisconsin (high-N-input environment). Symbols are comprised of a mean (horizontal line) and lower and upper 95% confidence intervals (end points of the vertical lines).
In Niger, the impacts of corralling cattle (dung plus urine) on millet yields are dramatically greater and longer lasting than the application of dung alone (figures 3 and 4(a)). The additional grain yield per hectare due to corralling cattle would satisfy the annual millet grain requirements of about 3–5 persons; the additional forage would provide an additional 480 to 580 days of feed for a typical dairy heifer. The application of dung plus urine by corralling heifers directly in fields for 2–4 days increased total forage DM by approximately 4600–5500 kg ha$^{-1}$ per year. This would provide an additional 480 to 580 days of feed for a typical dairy heifer.

3.3. Feed requirements to increase milk production (SSA)

Substantial increases in milk production seem possible in SSA if more feed N (as part of a N-energy balanced ration) is made available (figure 2). In Niger, an increase in annual milk production from current median of 560 kg AU$^{-1}$ to 1320 kg AU$^{-1}$ would require approximately 114 g of additional NI per day. This calculation assumes that each additional 1.0 g NI would produce 4.9 g of milk (calculated by dividing the additional 2.6 g of milk N per 100 g NI associated with the milk production increase of 560 kg AU$^{-1}$ (figure 2) by an assumed milk N concentration of 2.6 g kg$^{-1}$). The required additional 114 g NI per AU could come from cowpea (Vigna unguiculata) hay, a protein supplement fed to cattle and sheep in semi-arid West Africa. A nutrition trial conducted in Niger (Schlecht et al 1998) reported that a daily supplement of 1.4 to 1.8 kg of cowpea hay per cow increased dung DM output by approximately 30% and urinary volume output by 100% to 400%. Using the reported N concentration in cowpea hay of 30.4 g kg$^{-1}$, a somewhat similar 1.2 kg of cowpea hay per cow (320 kg live weight, table 1) would provide the additional 114 g NI required to increase annual milk production 560 kg AU$^{-1}$, and at the same time increase Nex (especially UN) which could be used to greatly increase millet food, forage and biomass production (figures 3 and 4(a)).

3.4. Feed reductions to decrease environmental N loss (WENAO)

In many WENAO settings, reductions in NI of dairy cattle would not greatly impact milk production (figure 2), but would reduce UN excretion and N loss. In Wisconsin, reductions in ration crude protein (CP = N × 6.25) concentrations from current state-wide average level of 175 g kg$^{-1}$ DM to 160 g kg$^{-1}$ DM (a level deemed sufficient for healthy, high production dairy cows, Broderick 2003) would decrease NI by 100 g AU$^{-1}$ per day (without reductions in milk production). This strategy would decrease urea N excretion by approximately 25% and ammonia and nitrous oxide emissions from dairy manure by 18% to 30% (Powell et al 2014).

Although reductions in feed N would reduce UN excretion and N emission, this practice may also decrease the fertilizer N value of manure, crop yield and manure N use efficiency. For example, the application of dung from cows fed a diet containing high CP diet (184 g CP kg$^{-1}$ DM) provided higher levels of crop N uptake and yield than dung from cows fed CP adequate diet (151 g CP kg$^{-1}$ DM, Powell et al 2006). Overall plant-available N levels are also higher in soils amended with slurry from cows fed a higher CP diet (168 g kg$^{-1}$ DM) than in soils amended with slurry from cows fed a lower CP diet (155 g kg$^{-1}$ DM, Powell et al 2011b). Reductions in manure N availability to crops due to less NI could be compensated easily however with fertilizer N, which is inexpensive, more easily applied, and generally used more efficiently by plants than manure N.

![Figure 4. Impact of barn manure and cattle corralling on additional yields of millet for food, feed and soil conservation in Niger (a) and feed in Wisconsin (b). Dashed lines above bars represent SE of means for total DM. Numbers within white 'food' bars refer to number of additional adults per year supported by the increases in millet grain. Numbers in black 'forage' bars refer to number of additional feed days that increases in forage DM would provide.](https://example.com/figure4.png)
4. Conclusions

Dairy cattle herds in SSA and WENAO differ considerably in their structures, milk production and N use efficiencies. On a whole-herd basis, relatively fewer lactating cows and more male cattle are kept in SSA, where DMI, NI, milk production and NUE-milk are much lower than in WENAO. Additional feed N (as part of N-energy balanced rations) in many low-N-input dairy cattle systems of SSA could be used very efficiently to produce more milk, enhance manure quality and therefore the production of food, forage and biomass for soil conservation. Exceptional crop production gains seem possible through application of both dung and urine to soils by corralling livestock directly in fields between cropping periods. Reductions in feed N in many high-N-input dairy production systems of WENAO would reduce excretion of urinary urea and therefore reduce N losses, especially ammonia and nitrous oxide. In both SSA and WENAO corralling dairy cattle directly in fields captures urinary N, which enhances manure N recycling and crop yields. A more widespread practice of corralling would have to consider however other system impacts, such as milk production, herd health, reproduction, labor requirements, and animal security in outside corrals. System comparative analyses also need to consider the relative financial costs and benefits of corralling versus manure collection, storage, transportation and land application of dairy manure. The results of this study demonstrate how different approaches to feed and manure management in low-N-input and high-N-input dairy cattle systems impact milk production, manure N excretion, manure N capture and recycling, crop production and environmental N loss.

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