Dairy heifer management impacts manure N collection and cycling through crops in Wisconsin, USA

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A B S T R A C T

Escalating energy and fertilizer N prices have renewed farmer interests in methods that reduce manure management costs and enhance the fertilizer value of manure. At the same time, air quality legislation seeks to mitigate ammonia loss from animal operations. We compared two dairy heifer management practices on manure N capture and recycling through crops: the conventional practice of barn manure collection and land application, and corralling heifers directly on cropland. Heifers were kept in a barn for two (B2) or four (B4) days and manure was hauled to fields, or heifers were corralled directly on cropland for two (C2) or four (C4) days. Four successive manure application seasons, spring–summer (SS), fall–winter (FW), summer (S) and winter (W) were evaluated over 2 years. Each season was followed by 3-year crop rotations: SS and S by wheat (*Triticum* spp. L.), sudangrass (*Sorghum bicolor* (L.) Moench), winter rye (*Secale cereale* L.), corn (*Zea mays* L.), winter rye, and corn; and FW and W by corn, winter rye, corn, winter rye, and corn. Corralling resulted in 50–65% greater N applications than barn manure. In barn N losses (% of excreted manure N, ExN) were greater from B4 (30%) than B2 (20%). Apparent N recovery of applied manure N (ANR) by wheat ranged from 13% to 25% at the lower (B2 and C2) application rates and 8–14% at the higher (B4 and C4) rates. First-year corn following FW had ANR of 13–32% at the lower (B2 and C2) application rates and 9–20% of applied N at the higher (B4 and C4) rates. As a percent of ExN, ANR over the 3 year rotation from C2 was 50%, B2 35%, C4 30% and B4 22%. Overall results demonstrated that corralling dairy heifers on cropland reduces ammonia loss and improves urine N capture and recycling through crops.

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1. Introduction

Stanchion or tie-stall barns are the most common housing types on dairy farms in the USA that have small to medium herd sizes, mostly in the Midwest and Northeast regions (USDA, 2004). On stanchion dairy farms, cows are confined to stalls that contain bedding, and manure is removed daily and stored for 2–4 days in manure spreaders before land application. Cows have access to bare-soil and/or partially vegetated outside areas, or may be allowed access to a pasture to graze for part of the day. On Wisconsin dairy farms, relatively less manure is collected from stanchion than free-stall barns, and manure collection is relatively lower on farms having small to medium herd sizes than on farms having large herds (Powell et al., 2005). Lactating cows, dry cows and heifers spend 10%, 30% and 80% of their annual time,

respectively in outside areas where manure goes uncollected. The average annual manure N loading rate in outside areas was 1200 kg ha^{-1} (range of 640–3600), manifold greater than agronomic requirements, and therefore a wasted resource, especially in the current era of escalating fertilizer N prices. A few farmers reportedly rotate outside areas with crops and pasture to take advantage of perceived enhancements in soil productivity due to cattle corralling (Powell et al., 2005). No information is available on the impacts of outside, cattle holding area management on soil properties and crop yields.

Dairy cows produce a lot of urine, which can be transformed rapidly into ammonia gas. Only 20–30% of the N (crude protein) fed to dairy cows is converted into milk. The remaining feed N is excreted about equally in urine and feces. Lactating dairy cows, dry cows and heifers annually excrete approximately 130, 80 and 50 kg N (Nennich et al., 2005, 2006). About three-fourths of the N contained in urine is in the form of urea. Urease enzymes, which are present in feces and soil, rapidly hydrolyze urea to ammonium, which can be converted quickly into ammonia. Gaseous ammonia losses from dairy operations begin to occur immediately after manure N excretion, and continue through manure handling,

Table 1
Heifer bodyweight (BW), dry matter intake (DMI), N intake (NI) and N excretion (ExN) during 2-year manure application period.

Year	Manure application season[a]	Heifer characteristics[b]			
		BW (kg heifer^{-1})	DMI (kg heifer^{-1} d^{-1})	NI (g heifer^{-1} d^{-1})	ExN
1	Spring–summer	429[c] (422–436)	9.1 (8.6–9.6)	222 (205–239)	216 (202–230)
1	Fall–winter	489 (482–497)	9.9 (9.5–10.3)	220 (211–228)	211 (209–214)
2	Summer	442 (430–454)	9.1 (8.6–9.6)	202 (188–216)	187 (170–205)
2	Winter	462 (451–474)	9.7 (9.1–10.2)	254 (241–266)	247 (238–255)

[a] Year 1 (2001–2002) spring–summer corresponded to April to September and fall–winter corresponded to October–March. Year 2 (2002–2003) summer corresponded to June to September and Winter corresponded to November, December, February and March.
[b] 48 heifers Year 1, 36 heifers Year 2.
[c] Mean, 95% confidence interval in parentheses.

storage and land application. Ammonia emissions from dairy barns range from 20 to 55% of manure N excretions (MWPS, 2001). The main factors that affect this value are housing and bedding type, frequency of manure removal, ventilation and temperature.

Before the advent of chemical fertilizer, farmers purposefully managed livestock and manure to maximize the capture and recycling of manure nutrients through crops and pasture. Such management continues in crop-livestock systems where fertilizers are too costly or unavailable. For example, to maximize the capture and recycling of manure nutrients, many African farmers corral cattle and sheep overnight on cropland between cropping periods. These practices, which return both feces and urine to soils, result in two to three-fold increases in crop yield than if barn manure only were applied (Murwira et al., 1995; Powell et al., 1998). The positive effect of livestock on crop production can last for at least three years after corralling. In temperate regions, most studies of urine-N impacts on plant growth have been done on pastures and depict negative effects of urine on pasture growth and livestock grazing behavior.

Under current management practices, much energy and labor is utilized to collect, haul and land apply dairy manure, and most urinary N is lost as ammonia, which reduces greatly the fertilizer value of manure. In the current era of escalating energy and fertilizer N prices, and new regulatory limits on ammonia emissions from livestock facilities (Aillery et al., 2006a; Aillery et al., 2006b), methods are needed that reduce manure management costs, enhance the fertilizer value of manure and reduce gaseous ammonia losses. The objective of this study was to compare two dairy herd management practices on manure N capture and recycling through crops: (1) dairy cattle housed in stanchion dairy barns and manure collected and land-applied on a regular (every 2–4 days) basis, and (2) corralling dairy cattle directly on cropland.

2. Materials and methods

The trial was conducted on a Richwood silt loam soil (fine-silty, mixed, superactive, mesic Typic Agriudoll) at the research farm of USDA-Agricultural Research Service's US Dairy Forage Research Center (USDFRC) in Prairie du Sac, WI; 43°19′N, 89°44′W. The experimental site was in continuous corn for the 5 years preceding this study.

Two manure application methods each at two application levels were evaluated: (1) the conventional method involved keeping dairy heifers in a stanchion barn and the manure produced during two (B2) or four (B4) days was hauled to fields; (2) the corralling method involved direct field application of feces and urine by keeping heifers on cropland in portable corrals for two (C2) or four (C4) days. Twenty manure application periods occurred during four seasons over a 2 year period: (1) a spring–summer (SS) season from May to September, 2001; (2) a fall–winter (FW) season from October to April, 2001–2002; (3) a summer (S) season during June to September, 2002; and (4) a winter (W) season from November to March, 2002–2003. A completely randomized block design was used each season to allocate three replicates of each manure treatment (B2, B4, C2 and C4) and three control plots to 6.3 m × 6.3 m field plots. Each manure application season was followed by 3-year crop rotations. A rotation of wheat-sudangrass-winter rye-corn-winter rye-corn was grown on plots that received manure during SS or S seasons, and a rotation of corn-winter rye-corn-winter rye-corn was grown on plots that received manure during FW and W seasons.

2.1. Dairy heifer and manure management

Approximately 2 weeks prior to each manure application, 48 heifers (SS and FW, Year 1) or 36 heifers (S and W, Year 2) approximately 16–18 months of age (Table 1) were selected from the farm herd. Heifers were weighed and then subdivided into two approximately equal weight groups. During Year 1, 24 heifers were assigned to a 'barn' group and 24 heifers to a 'corral' group. After determining higher manure N application rates (Table 2) Year 1 than originally planned, Year 2 heifer numbers were reduced to 18 for the 'barn' group and 18 for the 'corral' group.

The day prior to each manure application period the 'barn' group was subdivided into two equal groups of approximately equal bodyweight. One group was assigned to manure treatment B2 and the other to B4, then each group was moved to separate, newly cleaned and bedded barn stalls. Shredded wheat straw was spread evenly on barn floors at an initial rate of 1.5 kg per heifer.

Table 2
Manure N applications from heifers in barn for 2 (B2) or 4 (B4) days, or corralled in field plots for 2 (C2) or 4 (C4) days.

Year	Manure application season[a]	Manure application (kg N ha^{-1})			
		B2	B4	C2	C4
1	Spring–Summer	329[b] (303–354)	643 (594–693)	494 (474–515)	988 (946–1029)
1	Fall–winter	359 (323–396)	693 (651–736)	479 (468–490)	960 (937–983)
2	Summer	247 (214–279)	444 (399–490)	288 (254–321)	594 (535–653)
2	Winter	378 (328–428)	615 (579–653)	379 (357–400)	756 (705–805)

[a] Year 1 (2001–2002) spring–summer corresponded to April to September and fall–winter corresponded to October–March. Year 2 (2002–2003) summer corresponded to June to September and winter corresponded to November, December, February and March.
[b] Mean, 95% confidence interval in parentheses.

Additional 1.5 kg of shredded straw per heifer was applied each morning thereafter. After 48 h the B2 heifer group was removed from their stall, after 96 h the B4 heifers were removed from their stall. Manure was scraped, removed from stalls, hauled and applied to field plots, as described below.

'Corral' heifers were separated into six groups (four heifers per group, Year 1; three heifers per group, Year 2) corresponding to three replicates for each of the C2 and C4 manure application methods, and transported in a trailer to their randomly assigned field plots. Heifers were confined to approximately 40 m² areas using portable metal corrals. After 48 h, the C2 heifer groups were removed from their field plots, and after 96 h the C4 heifer groups were removed from their field plots. The surface of the entire experimental areas remained untilled until just prior to planting the first crop, as described below.

2.2. Feed nitrogen intake and total nitrogen excretion

During the week prior to each manure period, daily recordings were made of the amount of feed offered and refused by each 'barn' and 'corral' heifer group. Approximate daily feed dry matter intake (DMI, kg group^{-1}) was determined, which was increased by 10% during the following manure period to ensure ad libitum feeding. For the B2 and B4 groups, feed was offered each morning. For the C2 and C4 groups, feed was delivered each morning to portable feed bunks. To enhance probability of equal manure distribution, bunker and water trough locations were relocated each day.

Total N excretion (ExN, sum of fecal N and urinary N) by each heifer group was determined as the difference between feed N intake (NI) and N retained in heifer bodyweight (ΔBWN) according to Eq. (1).

$$\mathrm{ExN} = \mathrm{NI} - \Delta\mathrm{BWN} \qquad (1)$$

NI was determined as the difference between feed N offered and feed N refused by a heifer group (Table 1). Feed N offered was determined by multiplying feed DM offered by its respective N concentration, and feed N refused was determined by multiplying feed DM refused by its respective N concentration. Heifers were weighed monthly, approximately 2 weeks before and 2 weeks after a manure period. Bodyweight gains (kg heifer^{-1} d^{-1}) were multiplied by body N concentration of 24.7 g kg^{-1} for growing Holstein dairy heifers (Marini and Van Amburgh, 2003).

2.3. Manure land application and nitrogen loss

For the 'corral' heifer groups, N applications to field plots (Table 2) equaled calculated ExN (Eq. (1)) during the 2 (C2) or 4 (C4) treatment days. For the 'barn' heifer group, manure was hand-scraped from stalls and placed into 136 L plastic bins. Bins were divided into three approximately equal weight groups, which corresponded to three plot replicates for each B2 or B4 manure application treatment. The day of collection, manure was transported and surface-applied manually to field plots. Hand-grab samples of manure were taken during application to each plot. Samples were stored in zip-lock plastic freezer bags and frozen immediately for later analyses.

Manure N applications (NAPP) to B2 and B4 plots (Table 2) were calculated by multiplying the wet mass (kg) of manure applied to each plot by its respective concentrations (g kg^{-1}) of dry matter (DM) and total N (TN). Data on ExN (Eq. (1)) allowed for estimating N loss (NLOSS) during the time between N excretion and land application. Monthly NLOSS was calculated as percentages of ExN according to Eq. (2).

$$\mathrm{NLOSS}\,(\%) = 100\,\frac{\mathrm{ExN} - \mathrm{NAPP} - \mathrm{bedding\,N}}{\mathrm{ExN}} \qquad (2)$$

where bedding N (g plot^{-1}) was the mass (kg) of bedding DM added to barn floors during B2 and B4 collection periods multiplied by its respective N concentration (g kg^{-1}). The relative accuracy of NLOSS and NAPP for the B2 and B4 treatments was assessed by comparing study estimates of ExN and urinary N (UN) to literature values of these parameters.

$$\mathrm{UN}\,(\%) = 100\,\frac{\mathrm{NLOST} + \mathrm{TAN}}{\mathrm{ExN}} \qquad (3)$$

where NLOST is (g plot^{-1}) the numerator of Eq. (2) and TAN (g plot^{-1}) is the total ammonical N applied to either B2 or B4 treatment plots. TAN was calculated by multiplying the wet mass (kg) of manure applied to each plot by its respective concentrations (g kg^{-1}) of dry matter (DM) and TAN (Table 3). This calculation assumed that dairy feces contained only small amounts of ammonium (Haynes and Williams, 1993) so that most of the TAN in applied manure was derived from urine.

2.4. Soil compaction measurements and tillage

Soil strength (cone penetration resistance) measurements were made with a constant-rate cone penetrometer with a 30° cone and 1.29-cm diameter base (Lowery, 1986; Larney et al., 1989). Data were collected with a Campbell Scientific 21X datalogger and transferred to an SM192 storage module (Campbell Scientific, Logan, UT). Using an 'x' design with the center being the measurement taken in the center of the field plot, five penetrometer measurements per plot were made to a depth of approximately one meter, just prior to tillage and planting. Penetrometer measurements were made in plots for 9 of the 12 manure months Year 1, and all 8 of the manure months Year 2.

Table 3
Yearly and seasonal dry matter (DM), total N (TN) and total ammonium N (TAN) concentrations in barn manure applied to field plots.

Year	Manure application season[a]	Concentrations (g kg^{-1})					
		Manure application B2			Manure application B4		
		DM	TN	TAN	DM	TN	TAN
1	Spring–summer	208[b] (197–218)	27.7 (26.4–28.9)	4.7 (3.4–6.0)	241 (223–260)	27.4 (25.4–29.5)	3.9 (3.2–4.70)
1	Fall–winter	199 (170–228)	31.5 (24.4–37.6)	11.0 (8.5–13.5)	266 (251–280)	21.7 (14.1–24.3)	5.6 (4.7–6.4)
2	Summer	192 (179–204)	24.3 (22.6–26.0)	6.1 (5.0–7.2)	242 (230–255)	26.0 (23.9–28.1)	5.0 (3.8–6.2)
2	Winter	192 (179–205)	34.1 (30.1–38.1)	14.1 (10.9–17.3)	237 (215–258)	28.3 (25.9–30.8)	7.4 (5.3–9.5)

[a] Year 1 (2001–2002) spring–summer corresponded to April to September and fall–winter corresponded to October–March. Year 2 (2002–2003) summer corresponded to June to September and Winter corresponded to November, December, February and March.
[b] Mean, 95% confidence interval in parentheses.

Tillage operations were performed either only during April (i.e., following FW and W manure applications) or during October (i.e., following SS and S manure applications). Manure therefore remained on plot surfaces for approximately 1–26 weeks prior to incorporation. Tillage included two passes with a chisel plow to approximate depth of 0–20 cm followed by two passes with an Aerway implement. Tillage was performed only prior to first crops in the rotation. Otherwise all subsequent crops were planted no-till, and weeds controlled as needed with Liberty[TM] and Roundup[TM].

2.5. Crop rotations, yields and N uptake

Three-year crop rotations followed each manure application season. After the Year 1 SS season, first crop winter wheat was planted in 38 cm rows in October, followed by sudangrass planted in 38 cm rows the following June, winter rye planted in 19 cm rows in October; corn planted in 76 cm rows in May; followed by winter rye (October) and finally corn (June). After Year 1 FW manure application season, first crop corn was planted in late-May, followed by winter rye, corn, winter rye, and lastly corn. The same crop rotations, similar varieties and planting dates were used following the Year 2 S and W manure application seasons.

Aboveground plant biomass was harvested from the innermost 9.3 m^2 of each 40 m^2 treatment plot. Wheat, sudangrass and winter rye were harvested with a flail forage harvester, and corn was harvested using a three-row research combine. Total biomass wet weights were recorded and samples were taken from each plot. Total plant N uptake was determined by multiplying plot total biomass DM by its respective N content.

Apparent manure N recovery (ANR) was determined using the difference method, which assumed that soil provides the same amount of N to all plots and that crop N uptake in plots that received manure treatments (B2, B4, C2, C4) in excess of crop N uptake in unfertilized control plots was the result of applied manure (Muñoz et al., 2004).

$$ANR = 100 \frac{\text{crop N uptake in treatment plot} - \text{crop N uptake in control plot}}{NAPP} \qquad (4)$$

2.6. Sample analyses

Samples of feed offered, feed refused and bedding were oven-dried (60 °C, 72 h) and ground to pass a 2-mm screen. Ground feed and bedding sub-samples were oven-dried (100 °C, 24 h) for DM determination, and analyzed for total N content by combustion assay (FP-2000 nitrogen analyzer, Leco, St. Joseph, IN). Manure samples were thawed and sub-samples were analyzed immediately for total N using a micro-Kjeldahl assay, ammonium N by distillation (Peters et al., 2003), and oven-dried (100 °C, 24 h) for DM determination.

2.7. Statistics

Statistical analyses were performed using the SAS statistical package (SAS Institute, 1990). The four manure application seasons were analyzed independently. Differences in response variables due to manure treatments were analyzed by generalized least squares analysis of variance, assuming period of manure application and field plots to be a random effects and manure application type (B2, B4, C2, C4), levels within a type (B2 vs B4, and C2 vs C4) and method (B2 + B4 vs C2 + C4) to be fixed effects. Where relevant, the protected least significant difference (LSD) test was used to determine significant differences among treatments at $P < 0.05$.

3. Results

3.1. Soil compaction

Barn manure applications (either B2 or B4) did not significantly impact soil compaction. Soil compaction due to corralling was generally limited to the upper 0–20 cm of the soil profile (Fig. 1), and depended on rainfall (Fig. 2) and the number of days of corralling. Three general soil compaction classes were delineated, based on percent deviation in average soil strength measurements (0–20 cm) in corralled plots relative to non-corralled control plots. Severe, moderate, and slight compaction (Fig. 1) occurred in plots having average soil (0–20 cm depth) strength measurements of >200%, 200–100% and 99–50% greater than average soil strength measurements recorded within the replicate's control plot. For the 9 manure application months that penetrometer measurements were taken Year 1, severe soil compaction occurred in plots where heifers were corralled during the April, June and July; moderate
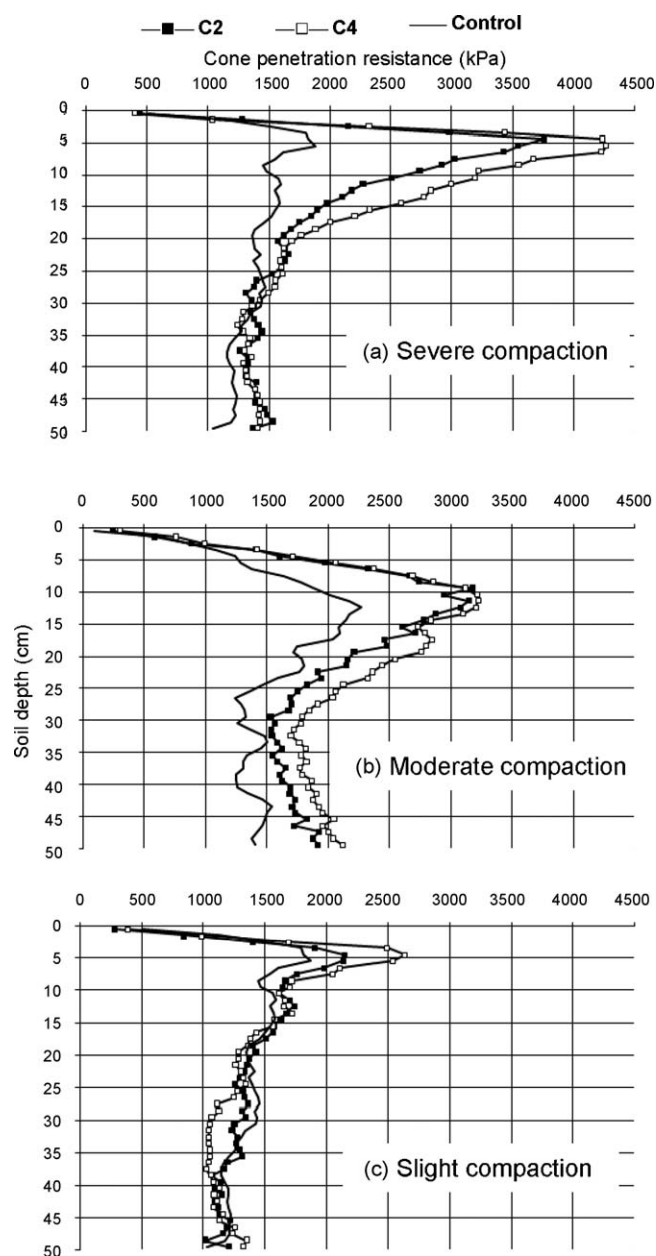

Fig. 1. Depiction of (a) severe, (b) moderate and (c) slight soil compaction after dairy heifers were corralled on cropland for 2 (C2) or 4 (C4) days.
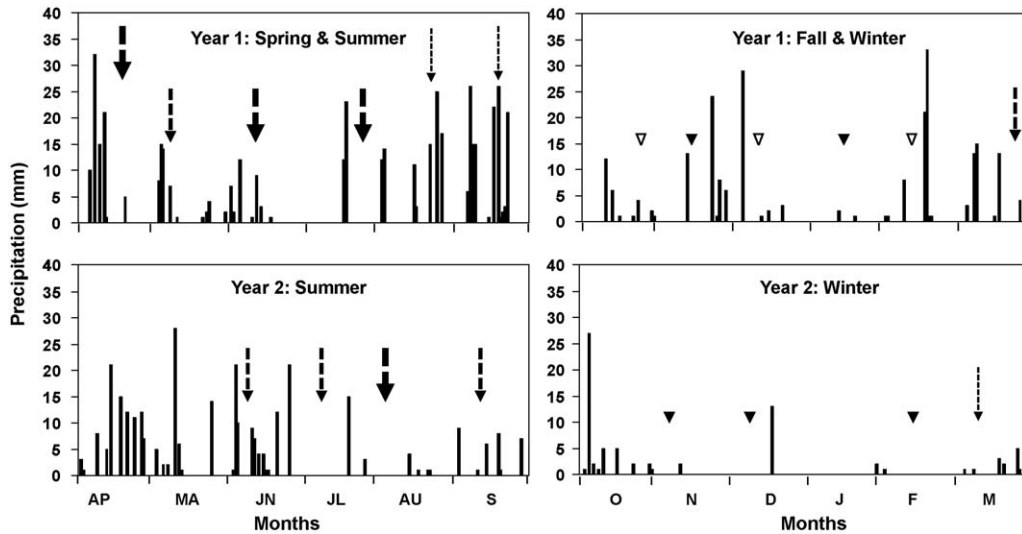
Fig. 2. Rainfall patterns in relation to heifer corralling and occurrence of soil compaction (arrows are centered between the second and third day of each 4-day corralling period. Solid arrows heads with thick, moderate and thin broken lines refer to the severe, moderate and slight compaction, respectively depicted in Fig. 1; solid arrow heads without lines signify no compaction; and open arrow heads without lines point to corralling period for which no compaction measurements were made).

compaction occurred during May and the following March; slight compaction occurred during August and September and no compaction occurred during November and January (Fig. 2). For the 8 manure application months of Year 2, severe soil compaction occurred during August; moderate compaction occurred during June, July and September; slight compaction occurred during March; and no significant compaction occurred during November, December and February. Except for Year 1 months of July and August, and Year 2 August, there were no significant ($P < 0.05$) differences in soil compaction between plots where heifers were corralled for 2 (C2) or 4 (C4) days.

Some soil compaction due to corralling appeared to be associated with precipitation just prior to or during the corralling periods (Fig. 2). For example, severe Year 1 soil compaction in April and June plots was likely due to rainfall the week prior to (April) and during (June) corralling. However, severe compaction also occurred during apparently dry periods in summer (e.g., Year 1 July, Year 2 August). Relatively low precipitation of late-fall and frozen soils of winter appeared to protect soils from compaction.

This study was not designed to assess the impact of soil compaction induced by livestock on subsequent yield. Soil tillage was designed to offset any impacts of soil compaction on establishment of subsequent crops. The large increases in soil penetration resistance that occurred on this silt loam highlight a potential problem with corralling livestock on crop fields. Further research is needed to determine whether such compaction has other detrimental effects, such as increased runoff on undulating landscapes.

3.2. Manure nitrogen applications

Corralling dairy heifers on cropland resulted in 50–65% greater N applications than housing heifers in barns and hauling manure to fields (Table 2). The greater manure N applications Year 1 were due to more dairy heifers (four per plot) used in this study year than were used (three per plot) in Year 2.

Differences in N applications with barn manure (B2 and B4) and corralling (C2 and C4) can be attributed mostly to volatile N losses (Fig. 3) in the barn and during manure transport to the field. Manure N losses were generally greater during spring–summer than during fall–winter periods. During most (75%) study months, relative (% of total ExN) N losses from B4 manure were greater than

from B2 manure. Of the total estimated ExN (Eq. (1)) in barns, approximately 20% was apparently lost during the 2 days (B2) and 30% during the 4 days (B4) that manure was excreted, collected and hauled to fields. Such losses correspond to a general range of 20–35% volatile N losses for dairy farms in the Midwest USA during daily manure scraping and hauling to field (MWPS, 2001).

Seasonal differences in volatile N losses from B2 and B4 (Fig. 3) were also evident in concentrations of TN and TAN in land-applied manure (Table 3). With the exception of B4 manure applied Year 1, average TN concentrations in manure applied during SS and S were 17% less than TN concentrations of manure applied during FW and W. For both study years, average TAN concentrations in SS and S manure were approximately one-half the TAN concentration in FW and W manure. Also for both study years, average TN and TAN concentrations in B2 manure were 14% and 64% greater, respectively than TN and TAN in B4 manure.

3.3. Manure impacts on crop yield and crop nitrogen uptake

Under prevailing soil and climatic conditions of central Wisconsin, most dairy manure impacts on crop yield and N uptake occur during the first season after manure application, although lesser impacts can continue over a longer period (Muñoz et al.,
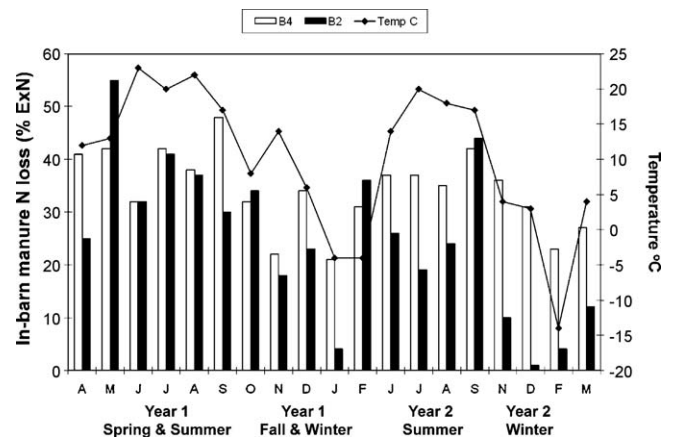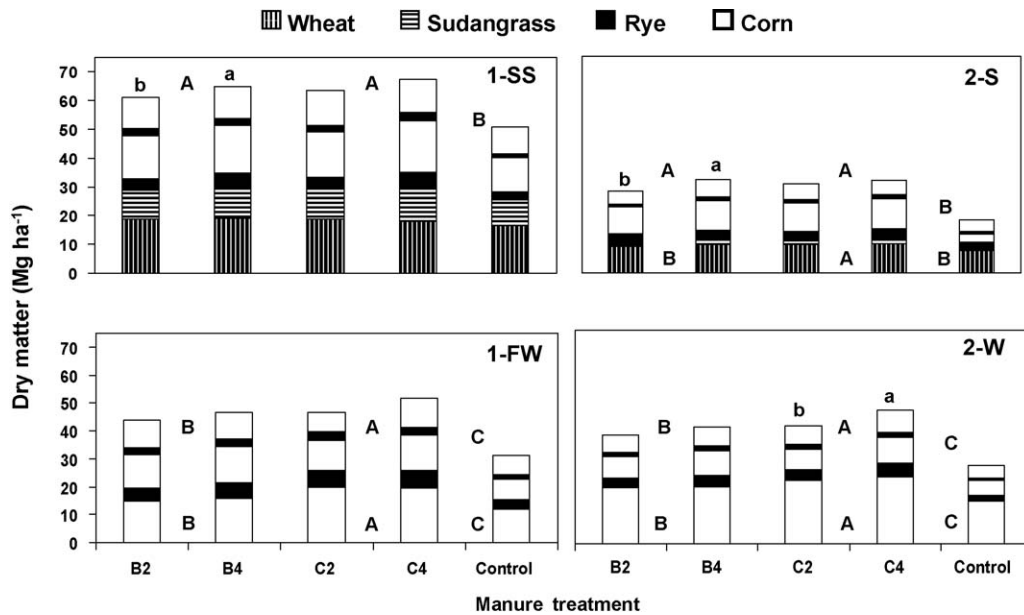

Fig. 3. Apparent N losses from B2 and B4 manure during manure collection and transport to fields.

Fig. 4. Manure treatment impacts on individual crop and total rotation yields. Rotations ascend from base of *x*-axis. Lower-case letters atop adjacent bars signify significant (*P* < 0.05) total rotation yield differences between adjacent treatments. Upper-case letters in middle of lower bars indicate significant first crop yields difference between composite barn (B2 + B4) manure, composite corral (C2 + C4), and control treatments. Upper-case letters in middle of upper bar portions indicate significant total crop rotation yields difference between composite barn (B2 + B4) manure, composite corral (C2 + C4), and control treatments.

2004; Cusick et al., 2006). For the present study, year, season, manure type and level were analyzed for their impacts on yields and ANR of first wheat and first corn crops, and total rotations.

After Year 1 SS manure applications, average wheat yields (Fig. 4) were similar in all four manure treatments and control plots. Wheat yields were also similar between average barn (B2 + B4) and average corralling (C2 + C4) treatments. Over the entire rotation, however, yield in plots amended with B4 manure were significantly (*P* < 0.05) greater than yield in plots that received B2 manure. Total rotation yields in C2 and C4 plots were similar. Also over the rotation that followed Year 1 SS manure applications, there was no statistical difference between yield in plots amended with barn manure (B2 + B4) compared to where heifers were corralled (C2 + C4). All manure treatments provided significantly greater total rotation yield than non-manured control plots.

After Year 1 FW manure applications, there were no significant differences in first corn yields between plots amended with B2 or B4 manure, or between C2 and C4 plots (Fig. 4). Average first corn yield in corral plots (C2 + C4) were, however, significantly greater than average corn yield in plots amended with barn manure (B2 + B4) followed by control plots. Similarly, total rotation yield in corral plots were significantly greater than yield in barn manure plots, followed by control plots.

Although yields following Year 2 S manure applications were much lower than after Year 1 SS manure applications (Fig. 4), patterns of manure treatment impacts were somewhat similar for both study years. After Year 2 S applications, wheat yields were similar in B2 and B4, and in C2 and C4. In contrast to Year 1 results, however, average wheat yield in corral (C2 + C4) plots were significantly greater than average yield in barn manure (B2 + B4) and control plots. Similar to Year 1 observations, total rotation yield in plots amended with B4 manure was significantly greater than yield in plots that received B2 manure. Total rotation yields were similar in C2 and C4 plots. Also over the rotation, there was no statistical difference between yield in plots amended with barn manure (B2 + B4) compared to where heifers were corralled (C2 + C4). Both manure application methods produced greater total rotation yield than control plots.

After the winter manure applications of Year 2, there were no statistical differences in first corn yields between B2 and B4, or between C2 and C4. Average corn yield in corral (C2 + C4) plots were significantly greater than average yield in barn manure (B2 + B4) plots. Control plots had lowest first corn yield. Total rotation yield in corral plots also was significantly greater than yield in barn manure plots, and control plots had lowest total rotation yield. Total rotation yields in C4 plots were significantly greater that those in C2 plots.

3.4. Apparent manure nitrogen recovery

One study objective was to determine whether timing of manure application impacted crop response to applied manure N. The SS and S manure applications were initiated 4–6 months before planting the first crop (winter wheat) and FW and W applications were initiated 5–6 months before planting corn. Whereas all dairy farmers in central Wisconsin spring-apply manure, manure is also applied year-round (daily haul system), and farms with storage apply manure during both fall and spring (Turnquist et al., 2006; Powell et al., 2007).

For all 20 possible manure application periods (Fig. 2) the timing of manure application had no significant impact on ANR for either the first crop (wheat or corn) or the total rotation. The likely reason for this impact is duration between manure application and planting. In all cases the last manure treatment was applied 14–20 days prior to soil tillage and planting the first crop. For surface applied dairy manure, most volatile N losses occur within a day after application (Jokela et al., 2008), and continue for weeks thereafter when solid manures are applied.

Of the eight possible ways to compare impacts of barn manure level on ANR by first crop wheat, corn or total rotations, four had significantly greater ANR at the lower (B2) than the higher (B4) barn manure application rate (Table 4). In no case was greater ANR obtained at the higher rate (B4) of barn manure application. The same eight same possible ways were used to assess impact of corral levels (C2 vs C4) on ANR. All eight possibilities displayed significantly greater ANR by first crops and total rotations at the lower (C2) than the higher (C4) corral levels.

Table 4
Manure treatment effects on percent apparent manure N recovery by first crops and total rotations.

Year	Manure treatment		Apparent manure N recovery (%)			
	Type	Application level	First crop wheat Spring–summer	Total rotation	First crop corn Fall–winter	Total rotation
1	Barn	2	22.7 a A	53.3 a A	13.5 B	48.0 a AB
1	Barn	4	14.5 b B	37.7 b B	8.9 B	29.0 b BC
1	Corral	2	17.0 a B	42.6 a AB	22.0 a A	49.1 a A
1	Corral	4	8.2 b C	29.1 b B	10.6 b B	26.0 b C
			Summer		Winter	
2	Barn	2	12.8 B	28.4 B	18.2 a B	35.7 B
2	Barn	4	10.3 B	29.0 B	12.2 b B	28.9 B
2	Corral	2	24.7 a A	45.6 a A	32.0 a A	55.9 a A
2	Corral	4	11.0 b B	25.2 b B	19.6 b B	38.7 b B

Within a year and manure type, manure application level ANR means followed by different lower-case letters differ $P < 0.05$; within a year, manure treatment ANR means followed by different upper-case letters differ $P < 0.05$.

All manure treatments had significantly greater ANR at the lower (B2 and C2) than higher (B4 and C4) manure application levels (Table 4). For wheat cultivated after Year 1 SS manure applications, highest ANR was obtained in B2 plots and lowest in C4 plots. For wheat cultivated after Year 2 S manure applications, and for the rotations that followed Year 1 and 2 SS manure applications, ANR was highest in C2 plots. For both first corn crops and both total rotations that followed Year 1 FW and Year 2 W manure application, highest ANRs were also obtained in C2 plots.

Calculations of ANR (Eq. (4)) provided estimates of the relative amount of applied N incorporated into subsequent crops (Table 4). Perhaps a more holistic assessment would be to calculate the relative amount of ExN (Table 3) apparently recycled through crops in the contrasting dairy cattle management practices of housing dairy cattle and hauling manure from barns (B2 and B4) versus corralling cattle directly on cropland (C2 and C4). Recalculations of ANR based on the relative amount of ExN incorporated into subsequent crops (i.e., replacing NAPP in denominator of Eq. (4) with ExN) would perhaps provide a more complete assessment of herd management impacts on the capture and recycling of urinary N through crops.

For the B2 and B4 treatments, the difference between ExN and land-applied manure N provided estimates of N losses during barn

Fig. 5. Relative amounts of total excreted N (Eq. (1)) unaccounted for and accounted for in total crop rotations (crops) and lost during manure collection and transportation (barn-N loss). Solid black bar portions having difference lower-case letters have significantly different crop N recoveries. Different upper-case letters signify that ammonia N losses are significantly greater from B4 than from B2 treatments.

manure collection and transport to fields (Fig. 3). After accounting for volatile N losses from barn-applied manure, relative proportions of ExN actually recycled through crops differed considerably among the manure application methods (Fig. 5). In all possible rotations, relatively greater proportions of ExN were recycled through crops after 2 days of corralling (C2) than after 4 days of corralling (C4) or the application of barn manure. Lowest proportions of ExN were recycled in B4 plots.
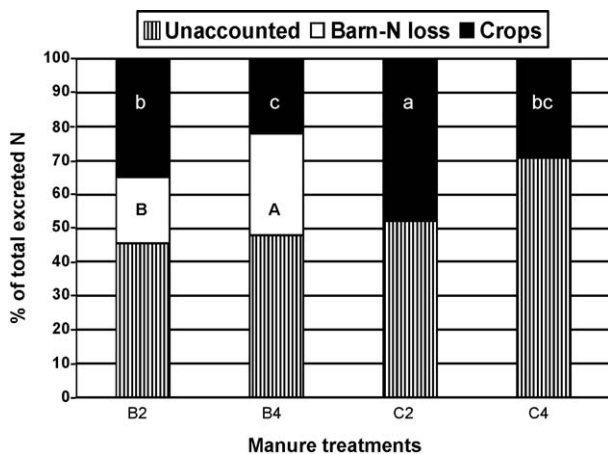
Lower ANR in plots amended with B4 than with B2 manure could be attributed to significantly greater amounts of volatile N loss (30.1% of ExN) in the B4 treatments than volatile N loss (19.5% of ExN) in the B2 treatments. These overall results demonstrate the importance of herd and manure management on urine N capture and recycling through crops. Corralling dairy cattle on cropland returns all ExN to the field, resulting in greater N applications (Table 2) and ANR of ExN (Fig. 5) than if cattle are kept in barns and only partial urine N recovery is possible.

4. Discussion

Estimates of ExN were calculated as the difference in NI and N retained in heifer body weight gain (Table 1). Calculated average estimates of ExN (215 g heifer^{-1} d^{-1}, Table 1) were higher than average ExN estimates of (183 g heifer^{-1} d^{-1}) from literature based on heifer body weights (Rotz, 2004; Wilkerson et al., 1997) or DMI and NI (Nennich et al., 2005), but compared more favorably (238 g heifer^{-1} d^{-1}) to studies conducted in the same location using similar feeds and heifers as the present study (Powell et al., 2008).

Total ammonium N (TAN) concentrations in manure provide an indirect measure of urine N conserved, and therefore the fertilizer N value of manure. In the present study, seasonal estimates of relative urine N excretions were calculated by adding the TAN contained in applied B2 and B4 manure to estimates of manure N loss (Eq. (3)). These calculations resulted in remarkably uniform estimates of UN, of which the average range of 49–51% compared very favorably to a range of 43–59% summarized from the literature (Powell et al., 2008). These favorable comparisons of ExN and UN to literature values provide confidence that estimates of these parameters provided accurate information on NAPP to field plots (Table 2) and ammonia N losses (Figs. 3 and 5) in our experiment.

Initial total N applications to field plots, especially during Year 1, were three to five times greater than local fertilizer N or manure N recommendations for winter wheat and corn (Laboski et al., 2006), but were within the range of overall N deposition in outside cattle holding areas (Powell et al., 2005). Average manure N

recovery by wheat ranged from 12.8% to 24.7% at the lower (B2 and C2) N application rates and 8.2–14.5% at the higher (B4 and C4) N application rates (Table 4). Average manure N recovery by first corn crops ranged from 13.5% to 32.0% at the lower (B2 and C2) N application rates and 8.9–19.6% at the higher (B4 and C4) N application rates. This pattern of lower manure N recoveries at high manure N applications has been reported (Muñoz et al., 2004) in central Wisconsin over the 3-year period that preceded the present study.

All four crop rotations had ANR that were approximately 2.5 times greater than ANR of first crops winter wheat and corn (Table 4). These results imply much greater availability of residual manure N than previously thought. Using ^{15}N-labeled dairy manure in central Wisconsin during the same time period as the present study, Cusick et al. (2006) determined that only 3–5% of applied dairy manure N was taken up by corn the second and third years after application. Thomsen et al. (1997) also estimated that only 3% of slurry N applied was taken up (by barley) the second year after application. A greater availability of applied N may have been due to numerous factors, such as a greater than anticipated immobilization of applied N, especially urine N, by the soil microbial pool, which became available during subsequent years. Also, the N contained in dairy feces and urine would have differential availabilities to subsequent crops. In corral plots, applied N appeared to be equally partitioned in feces and urine. Whereas urine N would be as available as fertilizer N, organic fecal N would become available in synchrony with soil microbial mineralization.

The present study found that corralling heifers directly on cropland recycled approximately twice the amount of ExN than barn manure applications. However, from 50% to 70% of N applied to corral plots and 45–50% of N applied as barn manure could still not be accounted for (Fig. 5). Some of the unaccounted for N was lost as ammonia during a 3–4-week period immediately after manure land application (losses quantified using a micrometeorological mass balance technique, Russelle and Powell, 2008), and some may have been lost via leaching and denitrification (Meisinger and Thompson, 1996). On average, 17–41% of the total N applied to B2 plots and 14–26% of the total N applied to B4 plots was in the TAN form (Table 3). The greater amounts of unaccountable N (Fig. 5) than TAN (i.e. the source of ammonia) implies manure N loss pathways other than ammonia volatilization likely occurred, and/or some of the applied N was immobilized by soil microorganisms.

5. Conclusions

This study demonstrated that dairy cattle management impacts manure N capture and recycling through crops. Approximately 20–30% of manure N excreted by heifers was lost during the conventional practice of scraping manure from barn floors and hauling manure to fields. Corralling heifers on cropland returned all manure N excretions to fields, resulting in greater crop production and overall N cycling than the conventional manure management practice. Whereas the present study demonstrated that corralling makes more efficient use of manure N, other impacts, such as milk production, herd health, reproduction, and labor requirements would have to be compared to conventional practices. System comparative analyses also need to consider the relative financial costs and benefits of corralling verses in barn manure collection, storage, transportation and land application.

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