Ammonia volatilization trends following liquid hog manure application to forage land

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ABSTRACT: Recent changes in the livestock industry of western Canada have included the increased establishment of intensive hog operations in semiarid regions where the availability of cultivated land for manure disposal is limited. Instead, permanent forage lands, including both tame pasture and native rangeland, are being considered for manure application. Given the inability of manure to be incorporated on these areas with cultivation, this study tested and successfully utilized static sorber traps as a relatively easy and inexpensive method to assess ammonia (NH_3) losses on forage lands following different rates and methods of liquid hog manure application. Comparisons among treatments indicated ammonia loss increased with rate of manure application, with relatively greater losses on tame pasture than native rangeland. Coulter injection resulted in less ammonia loss compared to surface banding, with the greatest benefit on tame pastures, presumably due to the lack of surface litter and associated abundance of bare soil, factors that would increase ammonia volatilization. We conclude that the use of injection is beneficial in reducing ammonia loss on forage lands, particularly tame pastures at greater rates of manure application, but concede the economic benefits based on the amount of nitrogen conserved may be limited.

Keywords: Ammonia, forage land, hog manure, injection, litter, rangeland, static sorber traps, surface banding

Comparative ammonia (NH_3) losses were assessed using static sorber traps on semiarid tame pastures and native rangelands following the application of liquid hog manure using either surface banding or coulter injection at varying rates. Historical changes in livestock production have included an increase in confinement feeding and larger concentrations of livestock (McKenna and Clark, 1970). These changes have arisen from economic factors and regulations aimed at reducing pollution. It follows that manure management must be done without excessive contribution to soil, water, or air pollution, and be compatible with efficient and timely crop production (Evans et al., 1977).

Profit maximization is a key factor that has helped lead livestock producers to the concept of manure management at minimum cost while remaining below a certain 'nuisance' level (McKenna and Clark, 1970). Nitrogen (N) conservation is of particular interest, as this nutrient is susceptible to volatilization (almost exclusively as ammonia) during manure storage and following field application. Jackson et al. (2000) estimated 70% of total hog manure nitrogen was volatilized following application, thereby contributing to diffuse air pollution. Moal et al. (1995) conducted studies on grass and cropland in France, and found that on average, 75% of ammonia losses from applied manure occurred within the first 15 hours following application. Braschkat et al. (1997) noted that wind speed, solar radiation, pH and manure dry matter content all influenced ammonia losses from manure applied to grasslands.

Management strategies that limit ammonia loss, including the use of injection, may lead to reduced adverse socioenvironmental impacts such as the emission of odor, and thus, lead to the development of more effective policies for handling liquid hog manure (Al-Kanai et al., 1992). In some situations, reductions in nitrogen loss have been attributed to the use of specialized application techniques (e.g.: Bittman et al., 1999; Sanderson and Jones, 1997). A study by Bittman et al. (1999) on irrigated tame pasture in British Columbia found the apparent recovery of mineral nitrogen from manure was 18% to 30% greater with drag-shoe (e.g., trailing shoe surface banding) than splash-plate (e.g., above-ground broadcasting) application. DeKlein et al. (1996) found injection of cattle manure into a sandy grassland soil in the Netherlands decreased ammonia volatilization and increased nitrogen utilization by the sward, although denitrification losses also increased unless a nitrification inhibitor was used.

Trends in intensive livestock production in Alberta. In Alberta and the other prairie provinces of western Canada, large-scale hog production facilities have been consistently expanding into less densely populated semiarid regions (Canada-Alberta Environmentally Sustainable Agriculture Agreement [CAESA], 1991). While such expansion may help prevent social conflict over aesthetics and odor, there are other emerging concerns. Annual croplands, the traditional outlets for liquid hog manure, are often unavailable in these areas, requiring alternative lands to be considered for liquid hog manure application. The widely available, but historically less productive, semiarid native rangelands and tame pastures adjacent to these operations provide a potential alternative outlet for liquid hog manure, but due to their permanent nature, generally require the use of low-disturbance application techniques. Tame pastures include those land areas converted to introduced forage cultivars since European settlement, while rangelands are areas of native vegetation that have never been plowed and seeded.

Although much research worldwide has been directed into developing improved guidelines for manure management, the majority of these studies have investigated the application of manure to cultivated land, particularly the effect of varying rates of manure on cultivated soil properties and crop yields (e.g.: Randall et al., 2000; Trehan and Wild, 1993; Sawyer et al., 1990). In contrast,

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research evaluating the impacts of nutrient application on forage lands have been less frequent, and addressed primarily rates of commercial fertilizer application, usually in mesic environments (e.g.: Kowalenko and Bittman, 2000; Vetsch et al., 1999; Bittman et al., 1997). Moreover, among previous forage-manure based research, most studies have investigated manure application to tame pastures (e.g.: Bittman et al., 1999; Schmitt et al., 1999; Sanderson and Jones, 1997; Gangbazo et al., 1995). The limited research done on nutrient addition to rangeland has generally involved either fertilizer (e.g.: Black and Wight, 1979; Johnston et al., 1967; Gillen and Berg, 1998) or the application of biosolids (Harmel et al., 1997). In general, specific information on the effects of manure application to native rangeland is lacking (Smoliak, 1965), as is information on the potential environmental benefits, including reduced ammonia loss, from using technologies such as injection.

As a result, this research evaluated comparative ammonia losses associated with liquid hog manure application to four semiarid forage lands, including tame pasture and native rangeland vegetation, in southeast Alberta, Canada. Specific objectives included the evaluation of ammonia losses from: 1) varying liquid hog manure application rates, and 2) different application methods, including surface banding and coulter injection. This information will contribute to our understanding of the role of utilizing injection technology for the safe and sustainable application of manure to forage lands, including native rangelands.

Methods and Materials

Study area and design. Manure application treatments were conducted on two tame pastures and two native rangelands 40 km east of Drumheller, Alberta, Canada (51°22' N, 112°13' W). Study sites were located near the transition from the Mixedgrass Prairie to the southern Aspen Parkland vegetation zone (Strong and Leggat, 1992), and represented a range of common soil and growing conditions from Dark Brown to Black Chernozemic soils (Agriculture Canada Expert Committee on Soil Survey, 1987). The region has a continental climate, with short, warm summers and long, cold winters, and a semiarid mean annual precipitation of 394 mm (15.5 in). The study area is also representative of the area wherein hog production is common and has been growing as an industry (CAESA, 1991).

Table 1. Mean (SD) soil characteristics in the 0 to 20 cm depth for each of the native and tame sites as sampled in September 1998, prior to manure application.

	Sites			
	Native rangeland		Tame pasture	
Constituent	Xeric Mixed Prairie: Dark Brown Chernozem (n=5)	Mesic Fescue Grassland: Black Chernozem (n=5)	Xeric Crested Wheat: Dark Brown Chernozem (n=5)	Mesic Meadow Brome: Dark Brown Chernozem (n=5)
[1] NH_4-N*	1.22 (0.72)	1.26 (0.54)	1.52 (0.77)	1.14 (0.37)
[2] NO_3-N*	0.72 (0.66)	0.22 (0.22)	2.96 (2.15)	2.94 (1.11)
[2] PO_4-P*	2.4 (0.6)	3.6 (0.9)	9.0 (2.6)	9.0 (2.8)
[2] K*	471 (60)	334 (64)	337 (96)	213 (93)
[3] SO_4-S*	9.98 (9.78)	4.24 (1.61)	5.04 (2.57)	2.48 (0.80)
[4] Exch. Ca**	8.0 (3.51)	8.46 (2.19)	10.8 (5.52)	8.46 (2.63)
[4] Exch. Mg**	3.44 (0.79)	3.24 (1.39)	4.02 (1.40)	1.44 (0.54)
[4] Exch. Na**	0.44 (0.67)	0.12 (0.07)	0.84 (0.67)	<0.1 (0)
[4] Exch. K**	0.89 (0.13)	0.69 (0.14)	0.64 (0.20)	0.47 (0.22)
[5] E.C. (dS/m)	0.34 (0.16)	0.12 (0.03)	0.56 (0.41)	0.13 (0.022)
[5] pH	6.6 (0.2)	6.3 (0.2)	7.0 (0.7)	6.6 (0.2)
[6] O.M. %	3.86 (0.67)	4.94 (1.22)	3.22 (0.82)	3.22 (0.97)
[7] Db***	1.28 (0.04)	1.09 (0.03)	1.28 (0.08)	1.28 (0.14)
[8] Total sand %	50.8 (1.3)	45.0 (0.6)	49.2 (0.9)	62.4 (0.2)
[8] Total silt %	29.9 (1.2)	38.3 (0.6)	29.4 (1.1)	20.4 (0.2)
[8] Total clay %	19.3 (0.4)	16.7 (0.1)	21.5 (0.9)	17.2 (0.0)

[1] Extractable by 2M Potassium Chloride Solution (McKeague, 1978)

[2] Extractable by Modified Kelowna Extract (Ashworth and Mrazek, 1995)

[3] Extractable by 0.001M Calcium Chloride Solution (McKeague, 1978)

[4] Exchangeable by Ammonium Acetate at pH 7.0 (McKeague, 1978)

[5] 1:2 Soil:Water Method (McKeague, 1978)

[6] Organic Matter by Loss on Ignition (McKeague, 1978)

[7] Bulk Density for mineral soils, cores taken with powered core sampler, corrected for coarse fragments (McKeague, 1978).

[8] Particle Size Analysis using the Hydrometer Method (McKeague, 1978).

*** Units are mg.kg^{-1}**

**** Units are meq.100g^{-1}**

***** Units are Mg.m^{-3}**

Native rangeland in the region is representative of a diverse mix of plant communities from xeric Mixedgrass Prairie to mesic fescue grasslands (Coupland, 1961). The two native study sites included: 1) an upland bench (Mixedgrass Prairie) consisting of a *Stipa-Agropyron* range type on a loam textured, Orthic Dark Brown Chernozemic soil, and 2) a mesic fescue grassland (*Festuca-Stipa* range type) community on a loam textured, Orthic Black Chernozemic soil. The tame pasture sites examined included: 1) a mesic meadow bromegrass (*Bromus biebersteinii* Roem and Schult)-alfalfa (*Medicago sativa* L.) pasture, seeded in the spring of 1997 on a sandy-loam textured, Dark Brown Chernozem, and 2) a 15-year-old xeric crested wheatgrass (*Agropyron cristatum* L.)-alfalfa pasture on a loam textured, Dark Brown Chernozem. The latter sites are hereafter referred to as the crested wheat and meadow brome sites, respectively. Study sites were within 15 km (9.32 mi) of one another to facilitate use of a common manure source. All sites were in good to excellent range condition, although the tame pastures had bare soil in excess of 10% (Blonski, 2001). On the native rangeland, litter was observed to be 1 to 2 cm (0.4 to 0.8 in) thick, and overlying an intact mulch layer. Soil characteristics at each site are summarized in Table 1.

Manure application treatments were established using a randomized block design with four sites, two in each type of forage land (tame pasture and native rangeland). Each site was internally uniform with respect to physical site conditions (e.g.; slope, aspect, and topographic position) and initial vegetation. Ten treatments were applied at each site consisting of combinations of five different target rates of liquid hog manure (10, 20, 40, 80, and 160 kg ha^{-1} NH$_4$-N) or (8.9, 17.9, 35.7, 71.4, 142.8 lbs ac^{-1} NH$_4$-N) using each of two methods of application (surface banded and injected), applied April 12 to 13, 1999. Each treated plot was 7 x 50 m (23 x 164 ft), oriented perpendicular to the slope of the site. Maximum slope was 2%. A one meter (3.3 ft) buffer strip was maintained between all treatment plots.

Manure treatments. The Prairie Agricultural Machinery Institute (PAMI) of Humboldt, Saskatchewan was contracted to apply the manure, as they possessed unique injection equipment capable of achieving accurate application rates. Manure was applied using a 3 m (9.8 ft) wide 'Green-Trac' applicator consisting of a pressurized tank with a distributor system that delivers liquid hog manure through a system of hoses to injector shanks that lie directly behind single vertical disk coulters spaced 25 cm (9.8 in) apart. During application, coulters cut 10 cm (3.9 in) into the soil and injector boots applied manure into the furrows. For this experiment, coulter spacing was always 25 cm (9.8 in). When liquid hog manure was surface applied, the coulter system was raised above the ground to provide adequate clearance (approximately 20 cm [7.9 in]), with the liquid hog manure then surface banded. This technique differs markedly from traditional splash-plate methods that occur higher above the ground surface and create more agitation and increased dispersion than the method we used, which was more suitable to small plot research trials. Machine speed and orifice diameters within the distributor were adjusted to obtain the various application rates, with pretreatment manure sampling and calibration used to determine applicator speeds.

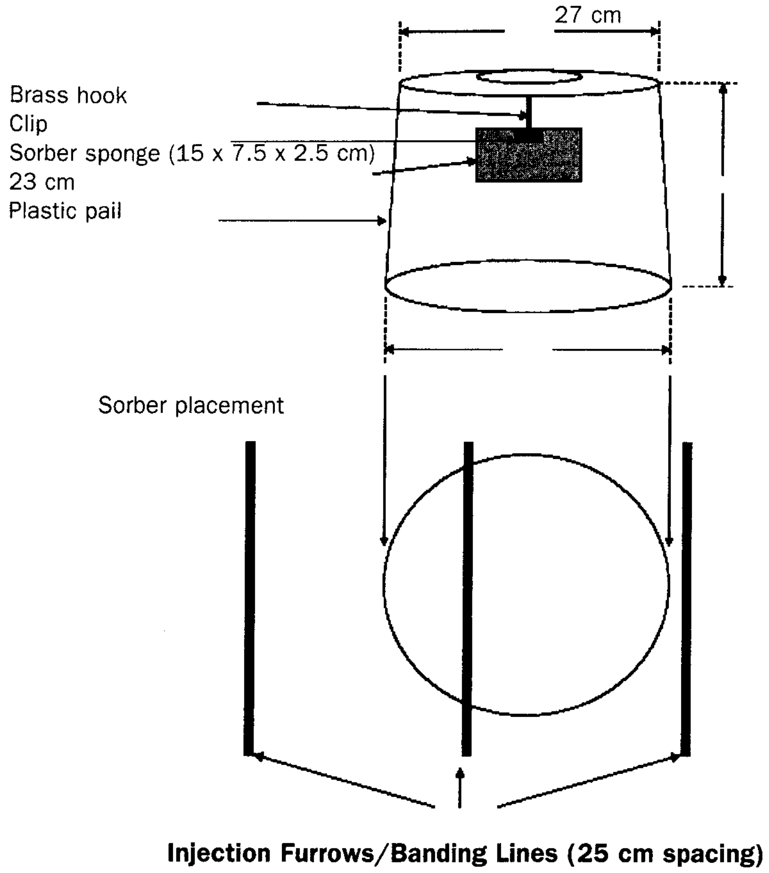
Preliminary samples of liquid hog manure were collected and analyzed for nutrient content to derive the appropriate bulk volume application rates (Alberta Code of Practice for the Safe and Economic Handling of Manures, 1995). Levels of bulk manure application varied with target application rates of ammonium-N (NH$_4$-N) (10, 20, 40, 80, and 160 kg ha^{-1}) or (8.9, 17.9, 35.7, 71.4, 142.8 lbs ac^{-1}), with actual bulk manure application rates (L ha^{-1}) adjusted for the NH$_4$-N content (0.21% NH$_4$-N) as determined by preliminary manure analysis. The liquid hog manure source was the first lagoon of a three-pit, nonagitated, uncovered lagoon of a 4000-head sow operation. The project cooperators use a nonagitated lagoon system as it reduces volatilization of odorous compounds and subsequent nutrient loss. Because all equipment and application rates were calibrated using samples from the nonagitated lagoon system, pits were not agitated prior to, or during liquid hog manure removal for treatment application. All liquid hog manure for application was removed from the lagoon in the same place near the center using an intake hose suspended from a float that allowed the hose opening to extract liquid hog manure from one meter below the surface. Manure was continuously agitated within the applicator during application. Additionally, the 10 kg ha^{-1} (8.9 lbs ac^{-1}) rate could not be achieved under normal operating conditions due to an excessive machine speed requirement. Thus, the 10 kg ha^{-1} (8.9 lbs ac^{-1}) rate was attained by diluting manure through a 1:1 mix with water (Table 2).

Previous research has indicated that hog manure is highly variable in composition, depending on characteristics such as age, dilution level, storage facility, location within lagoon, amount of solids, and odor treatment (Lorimor et al., 1997; Bayne, 1997). As a result, separate samples were collected from each truckload of manure applied to plots. After collection, all samples were immediately cooled to 4 °C (39 °F), and promptly tested for variability in moisture content, electrical conductivity (EC), pH, organic-N, nitrate-N (NO$_3$-N), NH$_4$-N, as well as total phosphorus, sulfur, potassium, calcium, sodium, and magnesium. Individual loads were highly uniform in characteristics, and mean percent (±SD) NH$_4$-N, NO$_3$-N, organic-N, total P, dry matter content, and moisture content were: 0.21 (±0.004), <0.01 (±0.000), 0.01 (±0.0008), 0.03 (±0.005), 0.60 (±0.060), and 99.4 (±0.060), respectively. Mean (±SD) pH and EC were 7.67 (±0.052), and 17.62 dS.m^{-1} (±0.098), respectively.

Static sorber traps. Estimates of ammonia loss on each of the 40 plots were made using two static sorber ammonia traps. Traps were constructed similar to the method used by Marshall and DeBell (1980) and Nason et al. (1988), who examined ammonia losses from urea applied to forest understories. However, due to the invasive nature of the liquid hog manure treatments to soils in this study, some modifications were necessary to facilitate use of static sorber traps on rangeland. Marshall and DeBell (1980) established traps by installing a connector ring into the ground, and applying urea pellets after the soil was allowed to equilibrate, after which the static sorber traps were put in place by fitting them into connector rings to form a tight seal. With the application of liquid hog manure to rangeland, it was not possible to preinstall connector rings, primarily due to the soil disturbance associated with the injection treatment and use of heavy equipment. Injection passes by heavy equipment would dislodge and destroy rings. To standardize sampling among all plots, rings were not installed, but instead traps were firmly pressed and twisted into the soil surface, approximately 0.5 cm (0.2 in). A tight seal was maintained between the trap and the soil surface using weights.

Construction of sorber traps involved the use of commonly available materials, including 11 L (2.9 gal) plastic pails, 27 cm (10.6 in) in diameter and 23 cm (9.1 in) deep (Figure 1). A 1.25 cm (0.5 in) brass hook was installed in the bottom center of each pail. Individual sorbers were constructed from 2.5 cm (1 in) thick polyethylene foam 15 cm wide by 7.5 cm tall (6 x 3 in). Sorbers were saturated with 75mL (2.5 fl oz) of 0.7 M (2.2 N) phosphoric acid in glycerol solution and allowed to drain under gravity until they contained approximately 50 mL (1.7 fl oz) of solution. Phosphoric acid (H_3PO_4) was used because it reacts with volatilized NH_3 to form ammonium phosphate ($NH_4H_2PO_4$) in the sorber sponge, which can then be extracted with deionized water and analyzed for NH$_4$-N in solution. Glycerol prevented desiccation of sorber sponges. Sorbers were prepared for installation, stored in airtight containers, and during installation were suspended from a clamp hung inside the inverted pail (Figure 1). Two replicate traps were set up within 30 seconds of the liquid hog manure application equipment passing through each plot. Traps were set up at random locations within each plot, but were always oriented centrally over the midpoint between the treated manure band/furrow itself, and the adjacent untreated interspace (Figure 1). The latter was done because sorber trap diameters (27cm [10.6 in]) differed slightly from the mean spacing between shanks on the applicator (25 cm [9.8 in]), thereby ensuring uniform sampling of both treated and untreated ground surface. Each trap was labeled with the time of placement, and remained in place for exactly 48 hours. The period was similar to the time exchange intervals used by Nason et al. (1988), and coincided with the disap-

Figure 1
Schematic of static sorber trap and placement in the field.



pearance of visible liquid hog manure moisture at the ground surface. Daytime high temperatures ranged between 12 to 15 °C (54 to 59 °F), while overnight low temperatures ranged between 3 to 4 °C (37 to 39 °F). Once traps were removed from the ground surface, sorber sponges were immediately placed in bags and any remaining air squeezed out prior to sealing. Precipitation was negligible during liquid hog manure application, static sorber trap set-up, and the 48-hour monitoring period that followed.

Ammonia was extracted from the static sorber sponges with three consecutive washings of 100 mL (3.4 fl oz) of deionized water. Extractions from the three washings were combined and analyzed for NH_4-N concentration in solution using a Technicon AutoAnalyzer II (1973). Concentrations were then converted to kg ha^{-1} (lbs ac^{-1}) of NH_3-N loss based on the soil surface area associated with each static sorber trap.

Statistical analysis. Data from all 80 sorber traps were analyzed using an analysis of variance (ANOVA) for a split plot experimental design (Steel and Torrie, 1980) to test the effects of the two types of forage land (tame pasture and native range), as well as the five liquid hog manure application rates and two application methods. Forage type was assessed using sites within each forage type as whole plots, with rate and method, their interaction, and all interactions with forage type assessed as subplots. Individual static sorber readings were considered to be sub-samples of sub-plots (n=2), and were treated as such in the analysis. Mean comparisons were conducted on all significant main treatment effects and their interactions using Tukey's mean comparison (Steel and Torrie, 1980). Significant rate effects were further evaluated using a series of contrasts to fully characterize their nature (Steel and Torrie, 1980). All differences were considered significant at $p<0.05$, unless otherwise noted.

Results and Discussion

Rate and method of liquid hog manure application significantly affected observed ammonia loss from treated plots (F=42.6 and 14.2, respectively; $p<0.001$). Despite only two whole plot replicates, forage type also affected ammonia loss (F=16.4; p=0.056), and furthermore, was found to interact significantly with both the rate (F=16.9; $p<0.0001$) and method (F=4.34; $p<0.05$) of manure application.

Utility of the static sorber ammonia traps. Results of this study indicate that static sorber traps were effective in detecting differences in ammonia loss among treatments. However, the method used to assess ammonia losses in the current study (static sorber traps) is unlikely to be as accurate as more elaborate but expensive procedures such as the integrated horizontal flux technique (McGinn and Janzen,1998). For example, sheltering of the soil surface directly below the trap from wind is likely to minimize measured ammonia loss by convection or drying. Ernst and Massey (1960) found that ammonia losses were directly related to increasing soil pH and temperature and that the loss of ammonia was closely related to the rate of soil drying and its initial moisture content. Sommer et al. (1991) also found that ammonia losses increased with wind. This effect may be offset, however, by the enclosed sorber trap functioning as a local ammonia sink, capable of drawing down ambient airborne ammonia, thereby potentially encouraging losses of ammonia from the soil surface. As a result, interpretation of the data is most appropriate between comparative treatment types (i.e., relative differences) rather than of absolute ammonia loss, and further validation would be needed to assess how closely the measured losses represent those occurring under field conditions. Marshall and DeBell (1980) compared several methods of monitoring ammonia loss from urea-treated forest soils, and detected progressively greater losses associated with the following techniques: closed-static chambers (13%), semi-open chambers (17%), and closed-dynamic chambers (22% to 26%), suggesting our values (i.e., closed static chambers) may be underestimated. However, Black et al. (1985) found comparable estimates of ammonia loss from semi-open chambers (24%) and the integrated horizontal flux method (25%) on pasture treated with urea.

The benefits of the sorber traps are in their ease of setup and application, and the relatively low cost of materials, labour, and laboratory analysis (total cost of approximately $800 Canadian for 80 samples).

Rate and forage type affects on ammonia loss. Contrasts of liquid hog manure application rate with measured ammonia loss indicated the increases in ammonia loss had a positive, linear ($p<0.0001$) association with incremental rates of liquid hog manure on both native range and tame pasture (Figure 2). The linear nature of this association indicated the relative risk of ammonia loss remained constant regardless of application rate. However, greater absolute losses at higher rates of application may increase the likelihood of other problems, such as the risk of exceeding localized odor tolerances of surrounding landowners and residents. The observed linear increases in ammonia loss were similar to other studies involving the application of fertilizer (Nason et al., 1988; Fenn and Kissel, 1973; Ernst and Massey, 1960), and liquid manure (O'Halloran, 1993; Sommer et al., 1991; Brunke et al., 1988; Beauchamp et al.,1982) or biosolids (Harmel et al., 1997) in North America.

The interaction of liquid hog manure rate with forage type resulted from relatively greater increases in ammonia loss on tame pasture, particularly at rates of 80 and 160 kg ha^{-1} (71.4 and 142.8 lbs ac^{-1}) NH_4-N (Figure 2), with overall ammonia loss on tame pasture 3.5 times that of native rangelands (Table 3). At the greatest application rate of liquid hog manure, measured ammonia loss was more than 4 times greater on tame pasture than native rangeland (Figure 2).

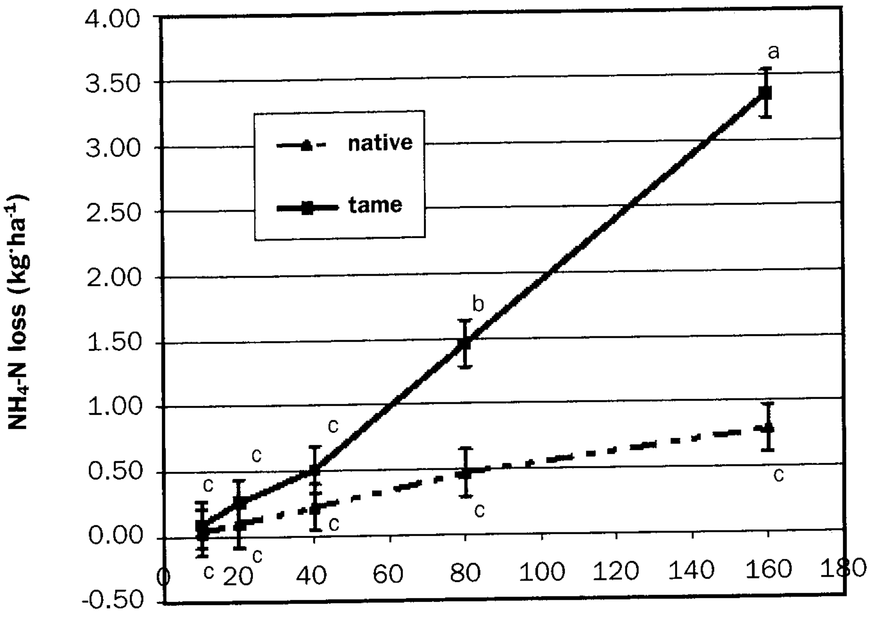
Although we expected some differences could have existed between the two mesic (fescue grassland and meadow brome) and two xeric (Mixedgrass Prairie and crested wheat-grass) sites, little difference was detected in mean ammonia loss between them (0.77 [±0.17] and 0.69 [±0.17] kg ha^{-1} N, respectively) or (0.68 [±0.15] and 0.61 [±0.15] lbs ac^{-1} N, respectively). These results suggested forage type rather than moisture status (i.e., landscape position) influenced ammonia loss across the study area.

Losses of ammonia were consistently lower on native range relative to tame pasture (Figure 2). The significant rate by forage type interaction reflected the increasing absolute difference in ammonia loss between forage types through greater rates of application (Figure 2). Average calculated losses of nitrogen on the tame pastures at the 160 kg ha^{-1} (142.8 lbs ac^{-1}) liquid hog manure rates were 3.35 kg ha^{-1} (2.98 lbs ac^{-1}), greater than the 0.79 kg ha^{-1} (0.70 lbs ac^{-1}) nitrogen loss on native range. These results indicate nitrogen conservation was increased by up to 76% when manure was applied to native rangeland rather than tame pasture. Differences in ammonia loss may be due to the greater abundance of litter and mulch on the surface of native rangelands. Tame pastures had been cultivated and reseeded in the last 15 years, reducing the amount of litter and increasing the fraction of exposed soil (Blonski, 2001). Low levels of litter increase wind velocity at the soil surface, thereby increasing water evaporation and ammonia volatilization. However, given that wind was essentially absent under the sorber traps, other factors may account for the differences in volatilization.

Native rangelands are uncultivated and have extensive litter and mulch layers (Weaver and Rowland, 1952) that contribute to rapid moisture infiltration (Naeth et al., 1991), reduced evaporation, and water conservation (Facelli and Pickett, 1991). The mulch layer on native sites also increases organic matter at

Figure 2

Measured NH_4-N* losses (kg.ha^{-1}) (± SE) on tame pasture and native rangeland following liquid hog manure (LHM) application at 5 different rates in April 1999. Means with different letters differ significantly ($p<0.05$).



*** NH_3 extracted from static sorber sponges with deionized water. Extractions were analyzed for NH_4-N concentration in solution, using a Technicon Auto-Analyzer II (1973).**

Table 2. Target and actual liquid hog manure (LHM) application rates and associated water depth equivalents.

Target application rate (kg.ha^{-1} NH_4-N)	Actual application rate (kg.ha^{-1} NH_4-N)	LHM application rate volumes (L.ha^{-1})	Water depth equivalent (mm)
10[1]	9.5	11 000	1.1
20	19.0	11 000	1.1
40	37.9	21 000	2.1
80	75.8	42 000	4.2
160	151.6	84 000	8.4

[1] Water Depth Equivalents and Application Rate Volumes for the 10 and 20 rates (kg.ha^{-1} NH_4-N) are the same because the Target Application Rate of 10 (kg.ha^{-1} NH_4^+-N) was achieved by mixing LHM and water at a 1:1 ratio.

Table 3. Measured mean NH_4-N* losses (± SE) in kg·ha^{-1} during the first 48 hours following LHM application on different vegetation types with varying manure application methods. Data represent pooled values across application rates.

		Manure application methods		
		Coulter injected	Surface banded	Combined methods
Vegetation type	**Site**	**Mean**	**Mean**	**Grand mean[2]**
Native range	Mixed Prairie	0.31 (0.18)	0.52 (0.18)	0.41 (0.12)
	Fescue Grassland	0.14 (0.18)	0.31 (0.18)	0.40 (0.12)
	Native mean	**0.23[1] (0.11)^{c}**	**0.42 (0.11)^{bc}**	**0.32 (0.14)^{B}**
Tame pasture	Crested Wheatgrass	0.65 (0.18)	1.26 (0.18)	0.96 (0.12)
	Meadow Brome	0.95 (0.18)	1.67 (0.18)	1.31 (0.12)
	Tame mean	**0.80 (0.11)^{b}**	**1.47 (0.11)^{a}**	**1.13 (0.14)^{A}**
Grand mean[2]		**0.51 (0.09)^{B}**	**0.94 (0.09)^{A}**	

[1] Within vegetation type by application method, those means with different lower case letters differ significantly at *$p<0.05$*.

[2] Within each of vegetation type and application method, grand means with different upper case letters differ significantly at *$p<0.06$*.

*** NH_3 extracted from static sorber sponges with deionized water. Extractions were analyzed for NH_4-N concentration in solution, using a Technicon Auto-Analyzer II (1973).**

the soil surface, provides soil surface insulation (preventing crusting), and promotes plant root and rhizome growth in the upper soil layers (Weaver and Rowland, 1952). In the current investigation, removal of this layer and exposure of bare soil on tame pastures was observed to result in both soil crusting, and subsequent manure ponding on the soil surface following liquid hog manure application, particularly at greater application rates. Manure ponding would increase the opportunity for ammonia volatilization to occur immediately following application. Notably, the removal of wind by the sorber traps suggests the differences in ammonia loss between native and tame forage types in this study may have been underestimated, as the presence of wind would have increased ammonia evaporative dispersal from ponded manure on tame sites (O'Halloran, 1993; Brunke et al., 1988).

The total amount of ammonia volatilized, even at the greatest liquid hog manure application rates (maximum 2.2% of total applied NH_4-N) represents a relatively small fraction of applied nitrogen. Other studies have indicated that ammonia losses may be as high as 99% of total applied nitrogen (O'Halloran, 1993; Lauer et al., 1976). Differences in the proportion of ammonia loss between studies may be due to differences in manure type, composition, length of storage times, and handling methods. In addition, differences may exist based on the types of vegetation and soils investigated, along with the inherent weather conditions during and after application, as well as the type of liquid hog manure application method, as discussed below.

Differences between application methods. The use of coulter injection rather than surface banding during liquid hog manure application generally reduced measured ammonia loss by as much as 55% (Table 3). The greatest ammonia losses were found on surface banded plots within tame pastures (Table 3), accounting for the significant method by forage type interaction. These results indicate the benefit of liquid hog manure injection in reducing ammonia volatilization was particularly prevalent on tame pastures.

The reduced ammonia loss with injection is likely due to the direct placement of manure into the soil matrix below the ground surface (up to 10 cm [3.9 in]) aiding adsorption of NH_4-N onto cation exchange complexes, and reducing opportunities for nitrogen contact with air, a necessary precursor for ammonia volatilization. Manure emergence onto the soil surface was observed during injection only when application rates reached 42 000 L ha^{-1} (4492 gal ac^{-1}), with the greatest emergence at 84 000 L ha^{-1} (8984 gal ac^{-1}), (the 160 kg ha^{-1} (142.8 lbs ac^{-1}) NH_4-N application rate). Within these treatments, a visual estimation of 10% and 40% of the ground surface was covered by liquid hog manure after treatment despite the use of injection.

Overall measured ammonia losses were reduced by 45% using coulter injection (Table 3). Although this reduction represents a savings in terms of plant nutrients, with associated benefits probable in terms of air quality (e.g., odor), any actual reduction in ammonia loss must ultimately be assessed against the added cost of the specialized equipment and the time (and labor) needed for application. Furthermore, the low detected capture of nitrogen using injection (i.e., 2 kg ha^{-1} [1.78 lbs ac^{-1}] at the greatest rate) in this study may not be indicative of actual nitrogen conservation. As discussed earlier, limitations in the ability of the static sorber method to measure actual ammonia loss restricts data interpretation to relative comparisons between treatments. Nevertheless, if one assumes that the 45% reduction in ammonia loss applies to actual field losses, the potential conservation of nitrogen due to injection appears substantial.

It is also important to recognize that the surface banded liquid hog manure application method used here (i.e., banded 20 cm [7.9 in] above ground) was markedly different from traditional splash-plate techniques. The latter method increases air-manure contact through increased manure agitation and atomization (Bittman et al., 1999; Sawyer et al., 1990), and may also increase runoff potential (Gangbazo et al., 1995). Additionally, splash-plate application distributes manure over a larger proportion of the ground surface. In contrast, surface banding occurred in isolated strips, and likely reduced the amount of ammonia that would be volatilized relative to conventional splash-plate technology. Thus, the observed levels of nitrogen conservation through the use of coulter injection are likely to be even greater if compared to conventional splash-plate application. Other intermediate methods of liquid hog manure application (e.g., punch aeration with broadcasting) may also have economic and practical benefits, but require comparative testing.

The finding that no method by rate of application interaction was observed suggests the benefits of using injection technology appeared to apply uniformly across all application rates. This finding was likely due to the consistently reduced area of ground surface affected by the injected treatment relative to those plots surface banded, even at the greatest liquid hog manure rate (i.e., 40% and 90% estimated surface coverage in the injected and surface banded plots, respectively). There was, however, a significant method by forage type effect, with greater reductions in ammonia loss from using coulter injection on tame pasture rather than native rangeland. On tame pastures with reduced litter and crusted soil, the use of incorporation methods such as low disturbance injection may have reduced the potential for ammonia volatilization by creating points of rapid entry and absorption of liquid hog manure into the soil matrix and reducing surface residence time (i.e., ponding).

Litter on native rangelands may also aid in nitrogen retention due to its tendency to conserve soil moisture (Willms et al., 1986). Increased moisture allows for rapid adsorption of NH_4-N (Tisdale et al., 1993). Native rangeland plant communities also have well-developed root systems and associated rhizospheric microbial populations (Dormaar and Willms, 1990), which in turn, may produce more organic matter and reduce soil bulk density, as well as serve as a sink following application. This may aid NH_4-N adsorption by roots, cation exchange complexes, and the soil as the more developed root systems of native plant communities increase soil porosity and create larger root channels that liquid hog manure can percolate into. Large, diverse microbial populations, in conjunction with complex root systems, may also immobilize NH_4-N, acting as slow-release fertilizer for later plant use following decomposition (Dormaar and Willms, 2000).

In contrast, tame pastures are primarily monocultures or simple polycultures that rely heavily on inputs such as fertilizer, cultivation, or periodic rejuvenation. These inputs, coupled with the simple composition of the plant community, may prevent the advanced development of diverse microbial populations or root systems that aid in retaining nitrogen from the liquid hog manure in the rhizosphere where it can benefit plant production (Dormaar and Willms, 1990). The use of an incorporation method such as low disturbance injection may also reduce ammonia volatilization by placing NH_4-N-containing liquid hog manure in direct contact with the soil, or more importantly, soil moisture, microbes, and plant root systems.

Summary and Conclusion

This field experiment demonstrated several promising outcomes in the overlapping spheres of livestock waste management and rangeland science. Static sorber traps offer a low cost, simple, and practical tool to compare the relative ammonia loss trends from liquid hog manure applied to native rangeland and tame pasture. Results from this field study also indicated there was a positive linear relationship between increasing liquid hog manure application rates and associated ammonia loss. In addition, estimated ammonia losses were greater on tame pasture than native rangeland, with the greatest effect evident at application rates at or above 80 kg ha^{-1} (71.4 lbs ac^{-1}) NH_4-N. In contrast, coulter injection of liquid hog manure decreased ammonia losses, particularly on tame pasture. Although economic factors will likely drive the adoption of injection technologies, other factors such as socioenvironmental considerations may become increasingly important determinants of future waste management plans for agricultural producers. Additional research is needed to quantify the actual ammonia losses on different permanent forage lands (e.g., soil types) with different methods of application and/or disposal, for use in more detailed cost-benefit analyses, likely using more sophisticated methods for measuring ammonia volatilization. Overall, these results indicate innovative application technologies such as coulter injection have implications for the reduction of odor, conservation of soil nutrients, and the integration of hog production with range and pasture management in semi-arid regions.

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Fifty years of crop evapotranspiration studies in Puerto Rico

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ABSTRACT: The water resources of Puerto Rico are currently being threatened by population pressure, development, pollution, and potentially adverse changes in the climate. Accurate determination of evapotranspiration is essential in managing water resources and practicing water conservation in Puerto Rico. In support of this goal, a review is presented covering the majority of research on crop water use and evapotranspiration estimation methods used in Puerto Rico during the last fifty years. Specifically, the review considers consumptive use determined from field water balance studies, calculation methods, and the pan evaporation method. Several studies also considered the estimation of reference evapotranspiration and the procedures for estimating climate parameter data needed as input to the reference evapotranspiration calculation methods. Recommendations for research priorities are provided.

Keywords: Crop water use, evapotranspiration, Hargreaves-Samani, pan evaporation, Penman-Monteith, Puerto Rico, reference evapotranspiration, U.S. Department of Agriculture-Soil Conservation Service (USDA-SCS) Blaney-Criddle

The countries within the humid tropics contain almost one-third of the total world population (Bonell et al., 1993). Within this region there are many small islands that rely on agriculture to feed their populations and whose water resources are subject to an ever-increasing risk. Therefore, it is imperative to better understand the hydrology of small tropical islands with the goal of improving water conservation practices. Since irrigation is one of the largest consumers of water in society, special emphasis should be placed on the development of techniques for estimating crop water requirements. In support of this goal, this paper reviews the majority of crop evapotranspiration studies conducted during the last fifty years in Puerto Rico with the hope that this information may be useful in Puerto Rico as well as in other areas of the humid tropics.

This paper is organized under the following headings: evapotranspiration reference materials, consumptive use obtained from field studies, studies predicting consumptive use, studies predicting reference evapotranspiration, studies comparing the Penman-Monteith equation with other evapotranspiration methods, estimating climatic parameters for use with the Penman-Monteith equation, use of pan evaporation data for estimating consumptive use, and peak

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