Final Report

Title: Controlling Odor and Nutrient Losses to Surface Runoff, Groundwater and Air with New and Conventional Manure Injection Technologies on No-Till and Sod Soils

Date: August 2009

SUMMARY

Improved management of manure application is widely seen as critical to the health of the Chesapeake Bay, but few alternatives to broadcasting manure have been adopted by farmers in the Bay's Watershed. We evaluated an array of manure application equipment for use in the watershed, from which we derived recommendations for site-specific use and conducted demonstration activities to promote alternatives to broadcasting. Environmental and agronomic evaluations were primarily performed at two sites in Pennsylvania and Maryland. While nearly all alternatives to surface applying manure demonstrated some form of advantage to environmental impact or agronomic performance, the shallow disk injection technology provided the most consistent improvements; whole farm modeling indicated a $50/cow return on typical Pennsylvania dairy farms with adoption of shallow disk injection, largely a function of improved nutrient use efficiency. Demonstrations across the Bay Watershed, from New York to Maryland, reached at least 2,000 farmers, and the project was featured in CCA schools, professional conferences and news media. The success of this project served to launch similar projects within the region (e.g. Virginia Tech's manure injection initiative) and beyond (e.g., the University of Minnesota's manure management over tile drain initiative). New technologies are now being evaluated using the methods developed by this project and several of the most promising technologies evaluated by the project (shallow disk, aeration) are spreading across the Bay Watershed through recent grants that serve to sustain the efforts begun under this project.

ROCK SPRINGS, PA FIELD SITE

The Rock Springs, PA site, located on the Penn State University Rock Springs Agronomy Farm, served as the hallmark of the project, located on long-term no-till fields. Six treatments were tested on field scale plots at the site, with 3 replications of each treatment spread across three blocks located along different contours. In 2006 and 2007 dairy manure was applied with all technologies described below. In 2008 we changed from dairy to swine manure application at this site. Also, based on the experience with the high pressure injector which is best suited for grassed fields, rather than no-till corn (see below), this treatment was eliminated and the plots were used to increase replication.

MANURE APPLICATION TREATMENTS

Field scale plots were established for the following six treatments:

1) *Broadcast manure*: Manure was applied to the soil surface from a toolbar with 6 outlets placed above splash plates. Outlets were spaced 65 cm apart and were operated approximately 1 m above the ground for even distribution.
2) *Immediate incorporation of broadcast manure by tillage*: Plots were chisel plowed (~20 cm deep) and culti-mulched approximately 1 h after broadcast manure application.
3) *Solid tine aeration prior to banding of manure*: A Gen-Till aerator (Genesis Tillage, Hope, IN[1]) was used in 2006 and an Aerway aerator (Holland Equipment Limited, Norwich, Ontario, Canada) was used in 2007 and 2008. Both units had 18 sets of rotating, solid tines spaced 20 cm apart to create cavities in the soil. However, the Gen-Til unit had 3 tines per set while the Aerway had four. Each unit applied a band of manure (5-cm width) on the soil surface behind each set of aeration tines so that some of the manure infiltrated into the 6-cm deep aeration cavities.
4) *Shallow disk injection*: Six shallow disk injection assemblies (Yetter Avenger, Colchester, IL) were mounted on a toolbar and spaced 75 cm apart. Each injector unit included a 60 cm diameter cutting disk, behind which was placed the manure drop tube. The cutting disk was set to create a 10 cm deep slot. Two disc sealers trailed the cutting disk to close the slot.
5) *High pressure injection.* The Direct Ground Injection (DGI) system (Moi A/S, Orre, Norway) employs a pump to pressurize (~120 PSI) slurry (<12% solids) through ports that open and close during application. Ports are spaced 20 cm apart and are located within skis that slide over the soil surface with no steel implement to pierce the soil. The slurry pulses from nozzles with sufficient force to inject the slurry into the ground forming 5 to 10 cm deep cavities. Once in the soil, the manure injected into the cavity diffuses into the surrounding soil.
6) *Control*: Unmanured controls plots were maintained. Fertilizer N was applied at rate similar to the manure N rate to the control plot.

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[1] Mention of trade names does not imply endorsement by USDA.

Details of the general layout of the experimental site and of each field plot are displayed in figures 1 and 2, below.

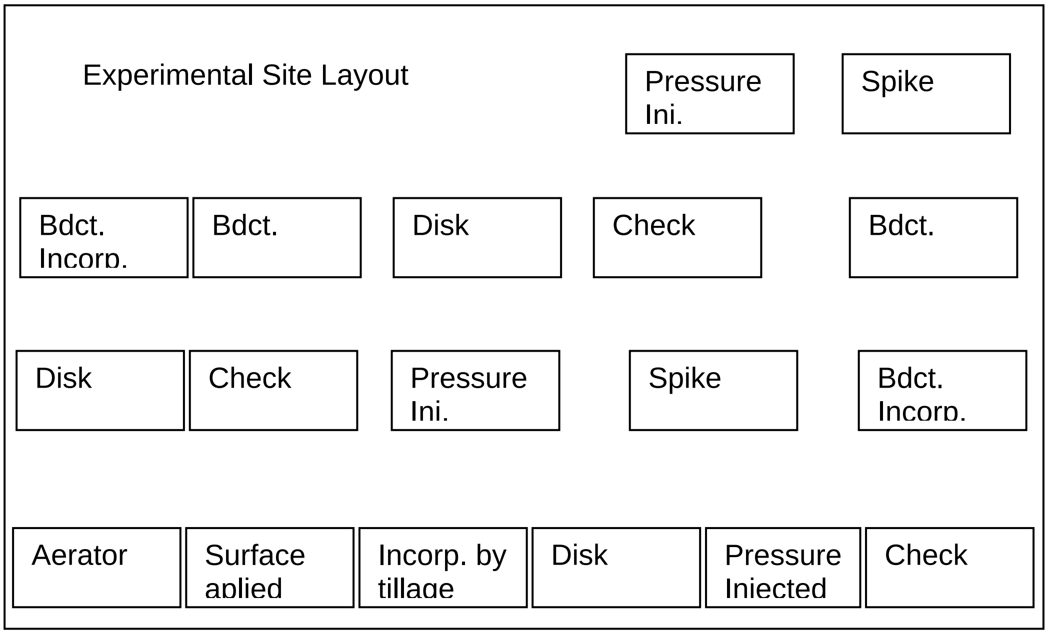


Figure 1. Experimental site layout and treatment plan.

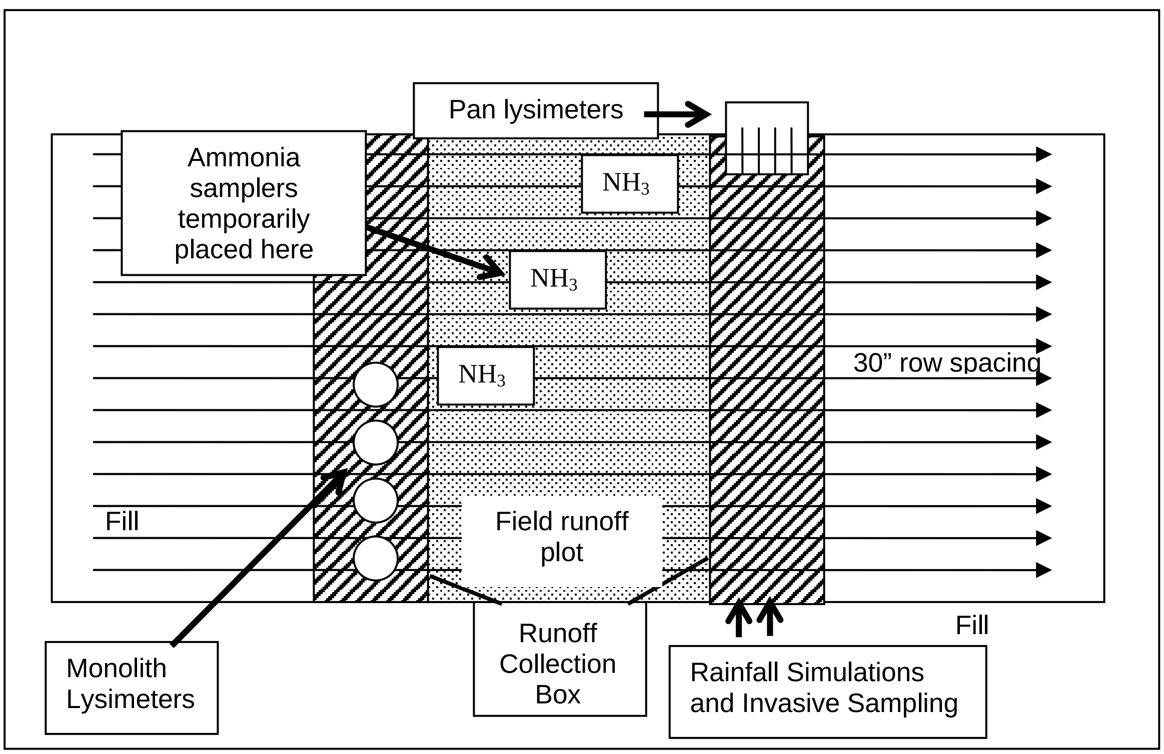


Figure 2. Layout of individual field plots.

Treatments were implemented on large field plots located on a relatively uniformly sloped (3-7%) Hagerstown silt loam soil. Each field plot contained three zones: 1, a central zone isolated by earthen berms where natural surface runoff was monitored and ammonia periodically measured using unobtrusive techniques; 2, a zone dedicated to invasive experimentation and sampling activities (rainfall simulation, soil sampling); 3, a zone where leachate was monitored by a transect of monolith lysimeters. A detailed soil survey was conducted of the site and extensive soil samples were collected at the onset of the study in 2005.

RESEARCH MANURE SPREADER

In 2005, a research manure spreader (2000 gal tanker) provided by USDA ARS was adapted to apply manure wit the various technologies evaluated in the project. The spreader has interchangeable tool bars for uniform surface application, shallow disk injection, and spike injection. A tool bar with a high pressure injection system was also constructed for this spreader. Initially, getting this equipment operating was a major activity requiring extensive work until we were comfortable that the spreader would apply the manure with acceptable accuracy and precision needed for our research. Once we had the equipment working we conducted rate calibrations with each piece of application equipment prior to establishment of the plots. This put us behind schedule in the first year, but because of the major investment in time and money to establish this research site we wanted to be sure that the equipment was operating as desired before using it in the actual research plots.

Through funding provided by this project, we were able to build our own research manure spreader during 2006. This significantly reduced many of the difficulties encountered in the first year with the ARS manure spreader. We had less plugging of the machine, better manure flow control, built-in scales for calibration and rate verification, a better distributor and easier changeover between applicators. The same application systems were built into the new manure spreader so that the treatments began in year one were carried through the rest of the project. This spreader was used for the experimental treatment applications in 2007 and 2008.

ROCK SPRINGS MANURE APPLICATION

2005

Manure application treatments were applied the week of June 6, 2005. Dairy manure (*Bos Taurus*) from the free stall barn on a local farm was applied at 6000 gal/A with each of the above-referenced application methods using the ARS spreader. Manure analysis is given below in Table 1. The control plots did not receive manure.

2006

Liquid dairy manure from the same farm as 2005 was applied at a rate of 6000 gal/A to a Hagerstown silt loam with each of the application methods using the ARS spreader. Manure was applied to plots in the three blocks on April 27th May 1st and May 8th, 2006 respectively. Manure analysis is given below in Table 1. The control plots did not receive manure.

2007

Liquid dairy manure from the same farm as 2005 and 06 was applied at a rate of 6000 gal/A to a Hagerstown silt loam with each of the application methods using the new research spreader. Manure was applied to the three blocks of plots on May 4, 7, and May 14, 2007 respectively. Manure analysis is given below in Table 1.The control plots did not receive manure but did receive chemical fertilizer equivalent to the available N estimated in the manure.

2008

Liquid swine manure from the Penn State University Swine Farm was applied at a rate of 8000 gal/A to a Hagerstown silt loam with each of the application methods using the new research spreader. Manure was applied to replicate plots in the three blocks on May 20, 27, and June 2, 2008 respectively. Manure analysis is given below in Table 1.The control plots did not receive manure but did receive chemical fertilizer equivalent to the available N estimated in the manure.

Table 1. Average analysis of liquid dairy manure applied in 2005, 2006 and 2007 and liquid swine manure applied in 2008.

Application Date	Manure Type	Solids	Total N	NH_4-N	Total P
		%	g L^{-1}	g L^{-1}	
2005	Dairy	10.11	3.9	1.3	1.4
2006	Dairy	9.65	3.9	1.2	1.2
2007	Dairy	9.1	3.7	1.5	1.1
2008	Swine	3.1	2.5	1.1	1.3

AMMONIA VOLATILIZATION

Ammonia emissions were measured for 72 h after manure applications in May of 2006, 2007, and 2008 using the dynamic chamber technique. Immediately following manure application, dynamic ventilation chambers were installed to measure ammonia volatilization. With this method, passive diffusion samplers (PDS) were used to collect NH_3 both inside and outside of ventilated chambers. Ammonia flux rates from the soil surface area covered by the chambers is then calculated from NH_3-N concentrations within the chamber, concentration of ambient air entering the chamber, and the rate of air exchange. Three ventilated chambers, containing duplicate sets of each two types of PDS, were deployed in each experimental plot (Figure 2). In addition, two PDS holders (containing duplicate sets of each PDS type) were placed outside the chambers to determine NH_3-N concentration of the ambient air entering the chambers. Exposure time of PDS was controlled to prevent saturation of the collection filters and was increased with increasing time after manure application because of decreasing NH_3 emission rates. Samplers were changed at approximately 1.5, 5, 10, 20, 26, 34, 48, and 72 h after manure application.

Broadcast application of liquid dairy manure substantially increased NH_3 emissions relative to the unamended controls, while cumulative emissions from tilled plots were not significantly different from unmanured controls (Table 2). Disk injection reduced emissions following dairy manure application by 58 and 99% relative to broadcast application (Table 2) and emissions following swine by 72% (Table 3). Application of dairy manure with the pressure injector resulted in reductions in NH_3 emissions that appeared to be comparable to disk injection, however mechanical problems limited the number of replications (Table 2). Emissions following banding/aeration of dairy and swine manure produced mixed results. No reduction, relative to broadcast, was seen following aeration with dairy manure 2006, but emissions were reduced by 71 and 69% with dairy manure in 2007 and swine manure in 2008 (Table 2 and 3).

Table 2. Cumulative ammonia emissions for a 72-h period immediately following liquid dairy manure application.

Application method	Cumulative Emission (kg NH_3-N ha^{-1})	
	2006 (dairy)	2007 (diary)
Broadcast	62.6 (16.8) † c‡	64.8 (10.3) c
Broadcast/incorporated	11.5 (1.4) ab	9.3 (5.1) ab
Banded with aeration	78.1 (26.9) c**	18.9 (12.2) b
Disk injector	26.0 (10.3) b**	0.3 (0.4) a
Pressure injector	22.4 (5.9) b	28.0 §
Control	-0.1 (0.4) a	0.2 (0.1) a

**Emissions differed significantly between years.

† Values in parentheses are standard errors.

‡ Means within the same column accompanied by the same letter are not significantly different.

§ Measurements were taken from a single field replicate because a mechanical problem with the high pressure unit prevented manure application to the second replicate.

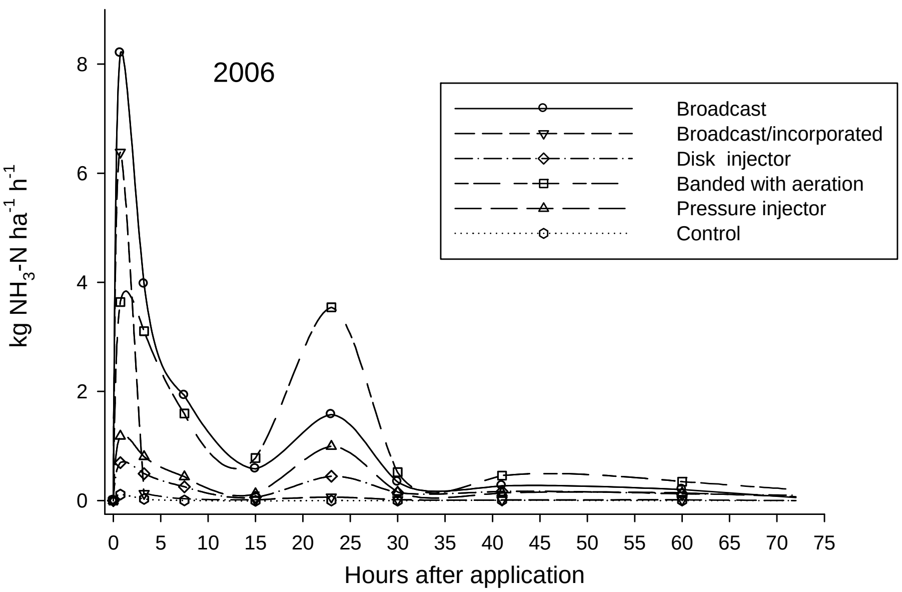
Table 3. Cumulative ammonia emissions for a 72-h period immediately following liquid swine manure application by three methods in 2008.

Application method	Cumulative Emission (kg NH_3-N ha^{-1})
	2008
Broadcast	46.9 (19.7)
Banded with aeration	14.6 (0.9)
Disk injector	13.2 (1.2)

Ammonia emission rates declined rapidly with time during the day of application (0-10 h after application), were low overnight (10-20 h after application), increased during the first sampling period of the second day (20-26 h after application), then dropped and remained low for the duration of the measurements (Data shown for dairy manure: Figure 3). Emissions from the broadcast/incorporated treatment dropped to essentially zero after tillage. While the drastic decrease in NH_3 emissions immediately following tillage is expected, our observations are an indication that the length of time between surface application and tillage will greatly impact the amount of ammonia loss. Delaying tillage by more than a few hours after manure application can greatly reduced the amount of N that can be conserved by tillage incorporation. Conversely, reductions in NH_3 losses are immediate and consistent with time following disk injection of the manures.

Disk injection provided the most consistent reduction in NH_3 emissions. Substantial reduction in NH_3 emissions following banding with aeration in two of the three years showed that this method, while less consistent than the disk injector, also has potential for substantially reducing emissions. Since manure incorporation following aeration is dependent on infiltration of manure into open holes, the impacts of soil conditions and manure properties can be expected to greatly impact the quantity of manure that moves below the soil surface. Relatively greater reductions in emissions following aeration in 2007 and 2008, compared to 2006, may have also been related to use of different aeration units. While side by side comparisons are needed, the three-tine aerator used in 2006 and a four-tine unit used thereafter may have different impacts on emissions.

Cumulative NH_3 emissions, regardless of the manure application method, generally increased linearly with an increase in the mass of manure remaining on the soil surface after application (Figure 4). While detailed analysis was performed only in 2006, our observations suggested that the absence of statistically significant differences between a manure application method and the control reflects effective incorporation of the manure. Therefore, the key to reducing NH_3 emissions is minimizing the quantities of manure left on the soil surface.



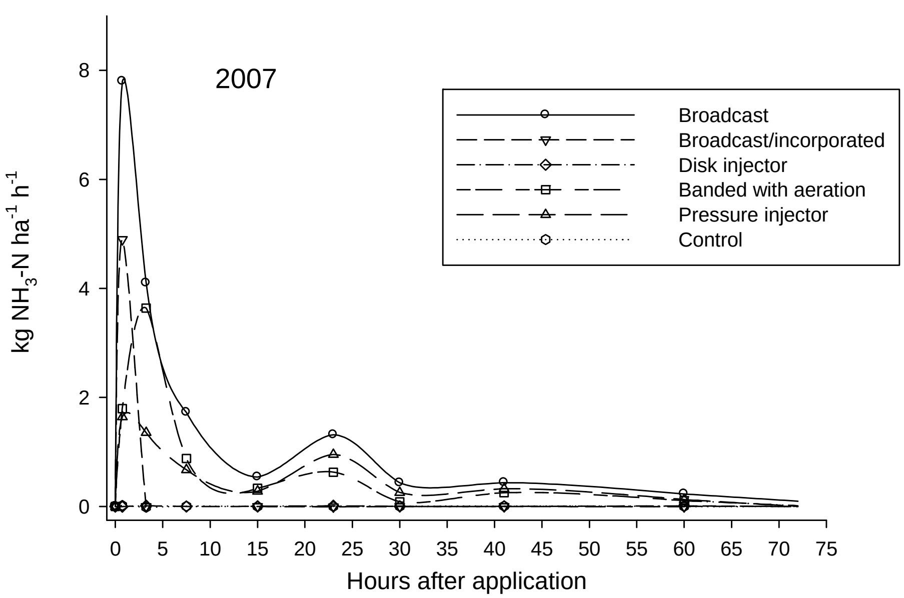


Figure 3. Ammonia-N emission rates over the 72-h observation period immediately following manure application by various methods in 2006 and 2007.

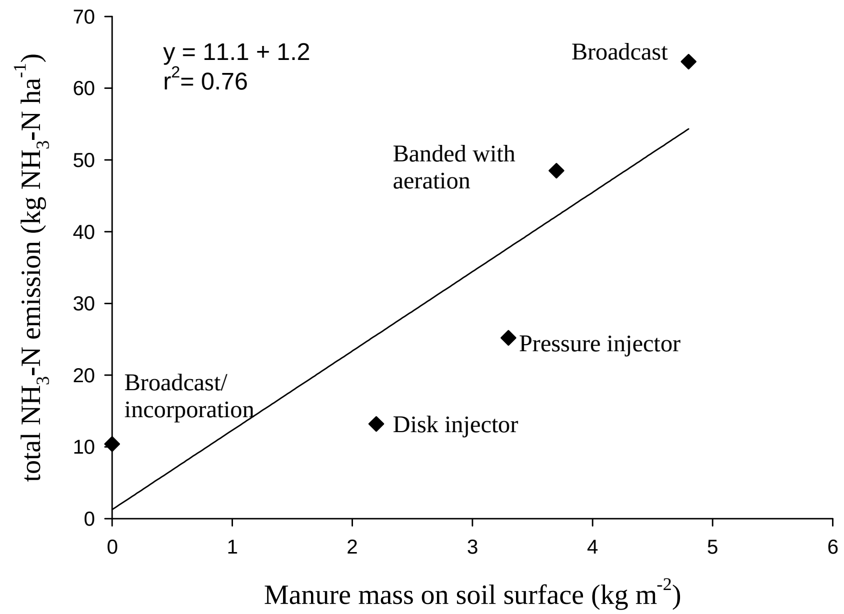


Figure 4. The relationship between total ammonia emissions and manure remaining on the soil surface following manure application by five methods.

ODOR EMISSIONS

Odor intensity measurements were conducted by a trained odor panel employing a Nasal Ranger ® scentometer in 2006 and 2007. To quantify odors, manure was applied along the perimeter of a 60-m diameter circle and measurements were made at time intervals relative to application time: prior; 1 hr after; 3 hrs after; 24 hrs after. Results were generally consistent with those reported for ammonia, and relative trends were similar between the two years, although the aerator performed considerably better at controlling odor emissions in 2007 than in 2006. As illustrated below for 2006 data (Figure 5), all manure application methods increased odor relative to the control after manure was applied. After 24 hrs odor intensity remained above background levels for all manure application methods. Most effective was the pressure injector, likely due to the fact that these observations were conducted on grass where the injector performs best (as opposed to no-till corn). Indeed, in the first hour after manure was applied the odor intensity of the pressure injector was barely above 7 dilutions to threshold, a common value used to delimit nuisance odor intensities. All other manure application methods, with the exception of broadcast manure, nearly lowered odor emissions to this nuisance threshold within 24 hours.

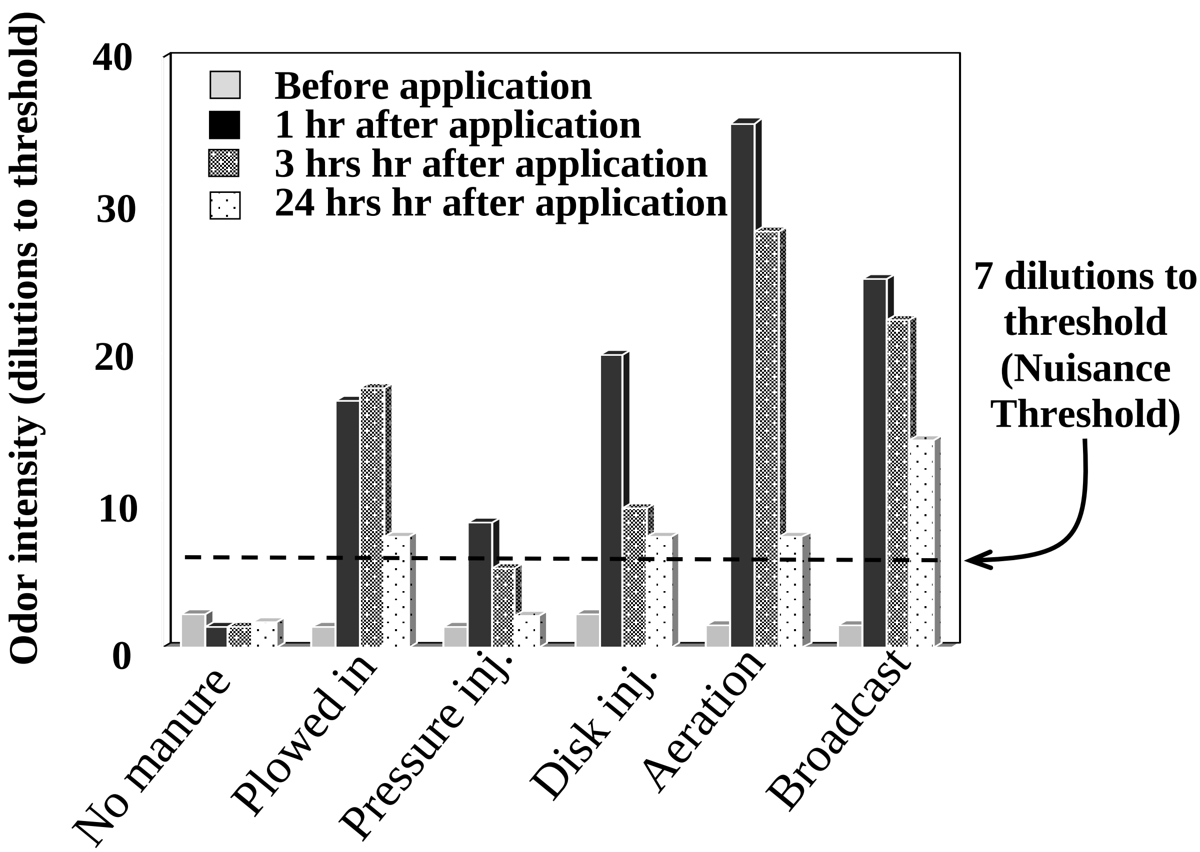


Figure 5. Odor intensities before and after manure application.

NITRATE LEACHING

In the spring of 2005, four column lysimeters were installed within one replicate field plot of each manure application treatment, except high pressure injection. Two lysimeters were installed in one replicate of the unmanured control. Lysimeters (30-cm diameter PVC, 60-cm deep) were buried 30-cm below the soil surface to allow manure injection and tillage operations over that area. Lysimeters were installed by excavating a trench using a backhoe, placing the lysimeters within the trench, backfilling the soil around the lysimeters, and finally replacing the surface 30 cm of soil back over the lysimeters. The bottom of each lysimeter was capped and freely drained to collection houses, where leachate was collected in plastic carboys. Lysimeter installation allowed for collection of water leaching below a 90-cm depth. Following leaching events, total volumes collected from each lysimeter were measured and water samples analyzed.

From January 1 through May 6, 2006, NO_3 leaching to 90 cm below the soil surface was similar for all treatments except the control, ranging from (37 to 51 kg N ha^{-1}). Nitrate leaching from the unmanured control plot during this same period was less than 40% of the leaching observed for any of the manured treatments (Figure 6). Flow-weighted mean NO_3-N concentration from the control (23.7 mg L^{-1}) was comparable to the other treatments (28.9 to 33.4 mg L^{-1}); however, water volume leached through the control lysimeters (5.8 cm) was less than half the amount of water leached from the lysimeters of the other treatments (12.8 to 15.1 cm). Despite similar NO_3-N concentrations across all treatments during the winter/spring of 2006, less water captured by the control plot lysimeters contributed to less total NO_3-N losses. Nitrate leaching from these plots during the winter/spring of 2006 can be attributed to previous cropping management practices and/or N mineralization and water movement through the soil profile during a period of low evapotranspiration.

After manure application in May 2006 and during that growing season (until September 30), NO_3 leaching was less than 11 kg N ha^{-1} for all treatments (Figure 6). While NO_3 leaching from the unmanured control plot was almost zero, greater leaching was observed from the treatments receiving manure. The small amount of NO_3 leaching during the growing season could be attributed mostly to differences in NO_3 concentration in the leachate. Nitrate-N concentration from the control plot was < 0.5 mg L^{-1}, while NO_3-N concentration was as great as 48 mg L^{-1} for shallow disk injection and as low as 10.6 mg L^{-1} for broadcast/incorporated. Water leachate volume ranged from 6.4 cm for broadcast/incorporated to less than 2.3 cm for shallow disk injection and the other two manure treatments. However, because there was so little water moving through the soil profile during the growing season, there was no consistent correlation between NO_3 leaching losses and losses due to NH_3 emission (Table 2).

Between October 1, 2006 and May 5, 2007, NO_3 leaching was much greater in the disk injected treatment than other treatments (Figure 6). An average of 52 kg N ha^{-1} was lost through leaching from the disk injected treatment compared to less than 13 kg N ha^{-1} for other treatments. Greater retention of N in soil due to the reduction in NH_3 volatilization (Table 2) with shallow disk injection of manure does not fully explain greater leaching losses from that treatment, since tillage incorporation also substantially reduced NH_3 emissions but resulted in leaching losses that were similar to broadcast application and banding with aeration. The greater leaching loss with the disk injector is likely also a feature of the placement of manure in a concentrated zone where the infiltration can be increased. Others have also recognized that NO_3 leaching was exacerbated by injecting N fertilizer into strips that were conducive to increased infiltration. An average of 23.7 cm of water leached below 90 cm with shallow disk injection during this period, exceeding water leached from any of the other treatment by 7.2 to 17.3 cm. Nitrate concentration was also slightly greater in the leachate with shallow disk injection during this period, 22 mg L^{-1} compared to 8 to 10 mg L^{-1} for the other treatments. Nitrate leaching was not observed during the 2007 growing season because of below normal rainfall.

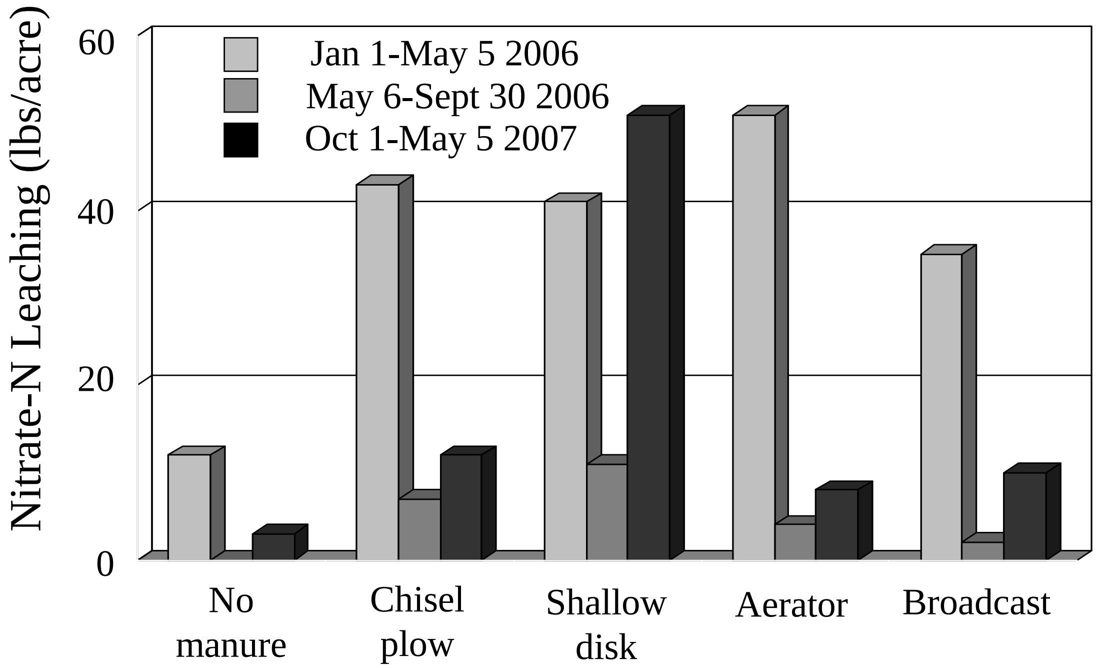


Figure 6. Nitrate-N leached through below-ground column lysimeters during the indicated time intervals. No leaching was observed during the 2007 growing season (May 6 to September 30). Error bars are the standard errors of the means of four lysimeters with a single field plot of each treatment.

PSNT AND CHLOROPHYL METER READINGS

PSNT

There was a significant difference in the PSNT levels in the 2006 growing season (Figure 7). The broadcast incorporated treatment had the highest PSNT. The disk injector PSNT was higher than the control but it was not different from the other treatments which were also not different from the control. One unexpected result is that the surface broadcast was one of the lower treatments, but the PSNT for this treatment was not significantly lower than any of the injection treatments. It was, however, lower than the broadcast incorporate treatment.

In 2007 and 2008 there were no significant differences between the treatments. In 2007 all of the treatments tested below the optimum level of 21 mg NO_3-N kg^{-1}. However in 2008, all treatments except the surface broadcast manure were greater than this critical level of expected response. The PSNT level for the control was significantly higher than the manure treatments but the PSNT values for this treatment should not be compared with the other treatments because this treatment received 100 lb N $acre^{-1}$ as ammonium nitrate fertilizer in 2008. Finally, the DGI injector was discontinued after 2006 therefore there is no PSNT data for this treatment in 2007-08.

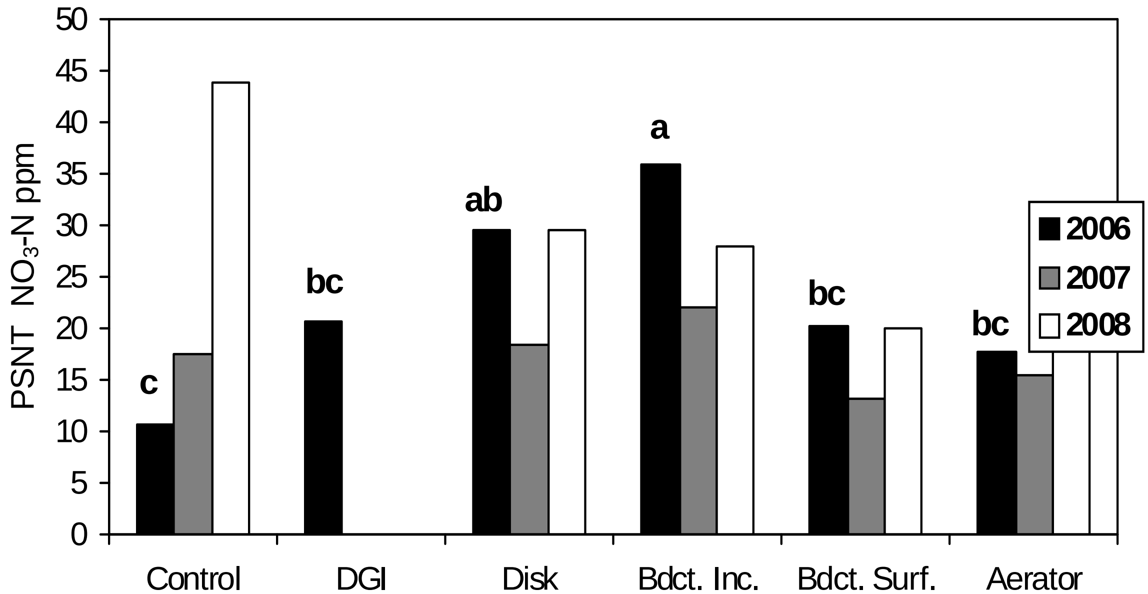


Figure 7. Presidedress Soil Nitrate Tests (PSNT) for the 2006-08 growing seasons. PSNT levels with the same letter are not statistically different at the 0.05 level of significance.

CHLOROPHYL METER

There was no significant difference in chlorophyll meter reading due to the treatments in 2006-08 (Figure 8). All of the chlorophyll meter readings were above the critical level of 46 where no response to N would be expected in 2007-08. However, in 2006 it was surprising that, while it was not significant, the broadcast incorporated treatment had numerically much lower chlorophyll meter readings than the other treatments. This is a questionable result because it is inconsistent with the rest of the results and with what would be expected from this treatment.

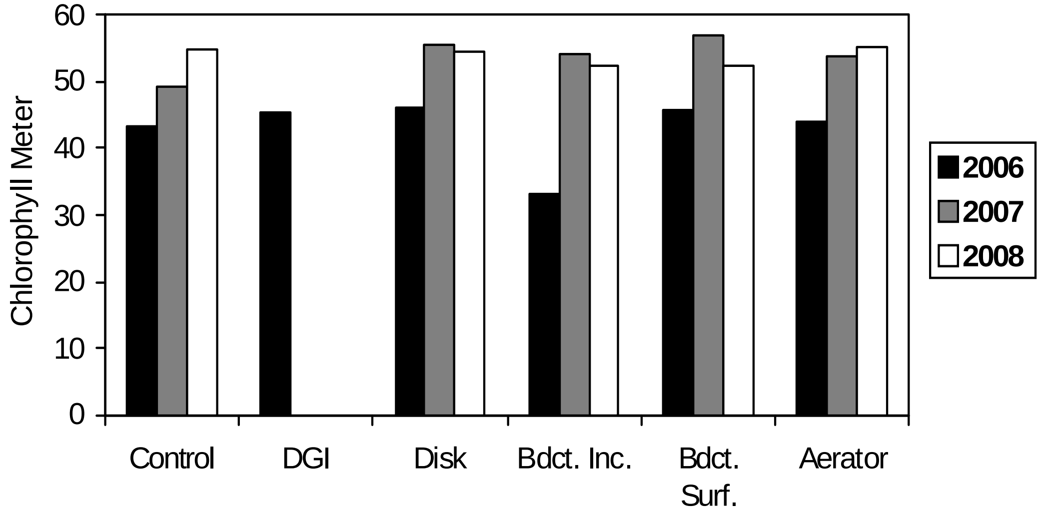


Figure 8. Chlorophyll meter readings at corn growth stage 6 for the different manure injectors and the control for 2006-08. Differences were not significant at the 0.05 level of significance.

RUNOFF

2005 RAINFALL SIMULATIONS

Two sets of rainfall simulation studies were conducted on all treatments by ARS and project personnel. The first set was run during the week of June 13, 2005 and the second set was run the following week. A portable rainfall simulator was used to generate uniform rainfall onto a 2 x 2 m area of each treatment plot using a standard protocol developed for the National Phosphorus Research Project. Runoff volume, sediment amount, particulate P, and soluble P loss were measured for each treatment. All runoff, soil, and manure samples will be collected, stored and analyzed according to standard procedures. Data on soluble and particulate P from the rainfall simulations are provided in the following graphs (Figures 9 and 10).

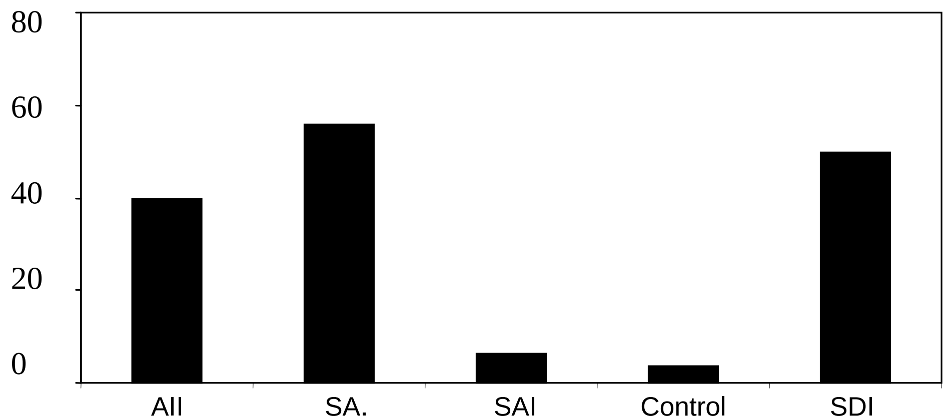


Figure 9. 2005 mean dissolved phosphorus concentrations (mg/plot) in runoff from small plots (2 x 2 m) for control, surface application (SA), surface application incorporation (SAI), aeration infiltration injection (AII), shallow disk injection (SDI) and pressure injection (PI)

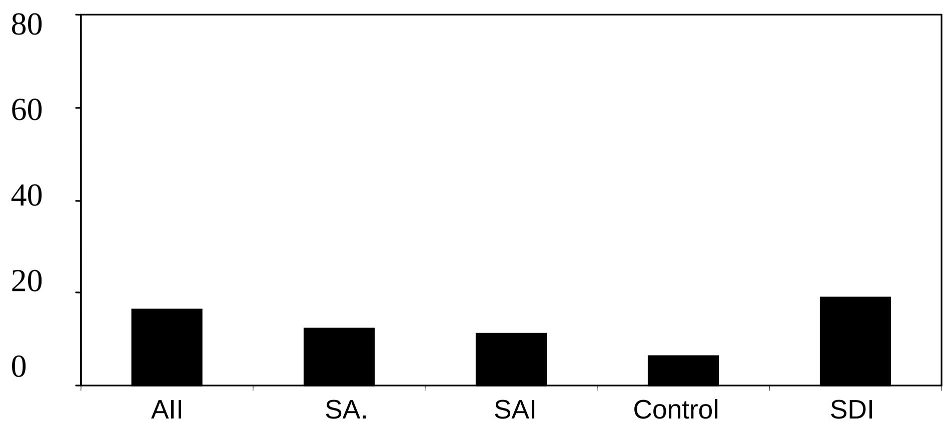


Figure 10. 2005 mean particulate phosphorus concentrations (mg/plot) in runoff from small plots (2 x 2 m) for control, surface application (SA), surface application incorporation (SAI), aeration infiltration injection (AII), and shallow disk injection (SDI)

Dissolve P losses for the aerator and disk injectors were not different from the surface broadcast treatment in these rainfall simulations. The chisel incorporated treatment and the check had much lower soluble P losses and were not different from each other. This data indicates that where there is some manure left on the soil surface after application there is a significant potential for soluble P loss in runoff. There was very little difference in particulate P loss between the treatments in these rainfall simulations. We expected to see higher particulate P loss from the chisel incorporated treatment but this was not observed.

Questioning 2005 rain simulation results. The use of these portable rainfall simulators has been well documented in the literature for estimating P losses. These simulators have typically been used to evaluate losses from a uniform area within the simulator. However, in the current research because we are using field scale equipment and the treatments by nature are not uniform over shorter distances eg. injection zones every 75 cm. Therefore the validity of using the portable rainfall simulator for this type of evaluation was questioned and these results from 2005 must be viewed with some caution until the question of the validity of the portable rainfall simulators is resolved. In 2006 and 2007 a much larger rainfall simulator was used to address this concern and to compare the two types of rainfall simulators.

2006 AND 2007 RAIN SIMULATIONS

To overcome the perceived limitations of using small plots (2 x 2 m) to evaluate runoff, rain simulations were conducted in 2006 and 2007 with the Water Erosion Prediction Project (WEPP) on larger plots (2 x 10 m runoff plots). Rainfall simulations were conducted on May 1^{st}, 4^{th} and 11^{th}, 2006 and on May 7, 10 and 18, 2007, approximately 3 days after manure was applied to replicate blocks of field plots. Rain was applied to field plots using #50 nozzles for at least 40 minutes and runoff was sampled every five minutes after runoff initiation. Runoff volume was determined and runoff samples were analyzed for total and dissolved phosphorus, and sediment. Along with differences in antecedent soil moisture and runoff depths, trends in P losses between treatments were variable over the two years although the lowest TP losses were consistently associated with the banded aerator treatment (Table 4).

Control (no manure). Losses of P in runoff from the control were among the lowest observed between treatments, averaging 11% of dissolved P and 31% of total P in runoff from the broadcast manure treatment for the two years of the study (Table 4). Only the banded aerator had losses less than the control in both years of the study. The low losses from the control clearly reflect the absence of applied manure and low concentrations of P in plot soils. Runoff from these plots had the lowest concentrations of dissolved and total P across the two years. Much of the P loss from the control was assumed to result from erosion, as dissolved P accounted for only 19 and 3% of total P in runoff from the control plots in 2006 and 2007, respectively. In 2007, the highest sediment losses were from the control plot, which were similar to the tillage treatment (chisel plowing) and significantly higher than all other treatments.

Table 4. Means and standard deviations (SD) for 2006 and 2007 rainfall simulations..

Tillage Treatment	N	Runoff † Depth (SD)	Concentration: Phosphorus DRP (SD)	Concentration: Phosphorus TP (SD)	Concentration: Solids TS (SD)	Load: Phosphorus DRP (SD)	Load: Phosphorus TP (SD)	Load: Solids TS (SD)
		----- mm -----	mg L^{-1}			kg ha^{-1}		
2006								
Control	2	2.34 (2.52) *a*‡	0.056 (0.04) *b*	0.46 (0.13) *b*	1.47 (0.74) *a*	0.0021 (0.0028) *ab*	0.011 (0.01) *c*	25.1 (19.7) *a*
Broadcast	3	0.52 (0.57) *ab*	1.83 (0.68) *a*	2.81 (0.81) *a*	1.79 (0.44) *a*	0.008 (0.008) *ab*	0.013 (0.01) *c*	10.0 (12.35) *a*
Broadcast Incorporation	3	0.33 (0.37) *b*	0.16 (0.18) *b*	1.45 (1.18) *ab*	3.94 (1.44) *a*	0.00019 (0.00006) *b*	0.008 (0.012) *c*	15.7 (21.6) *a*
Banded Aeration	3	< 0.0001 *b*	0.055 (0.0) *b*	0.16 (0.0) *b*	2.31 (0.0) *a*	<0.0001 *bc*	<0.0001 *d*	0.02 (0.04) *a*
Shallow Disk Injection	3	1.97(1.44) *ab*	0.34 (0.18) *b*	0.85 (0.17) *ab*	2.54 (0.99) *a*	0.008 (0.009) *a*	0.016 (0.011) *ab*	60.6 (46.7) *a*
Pressurized Injection	3	3.53 (2.48)*a*	0.17 (0.25) *b*	0.95 (0.17) *ab*	1.34 (0.49) *a*	0.009 (0.014) *a*	0.036 (0.03) *a*	48.3 (35.5) *a*
2007								
Control	3	23.1 (1.05)*a*	0.03 (0.03) *c*	0.76 (0.09) *c*	1.66 (0.64) *a*	0.0060 (0.006) *a*	0.172 (0.005) *a*	381 (139) *a*
Broadcast	3	19.6 (24.6) *ab*	2.46 (0.90) *a*	3.4 (1.28) *a*	0.44 (0.34) *c*	0.44 (0.59) *a*	0.88 (1.2) *a*	97 (137) *bc*
Broadcast Incorporation	3	7.43 (6.11) *ab*	0.10 (0.16) *c*	1.67 (0.28) *a*	4.08 (1.2) *a*	0.0051 (0.007) *a*	0.14 (0.12) *ab*	353 (380) *a*
Banded Aeration	3	1.06 (1.67)*b*	1.84 (0.50) *ab*	2.85 (0.42) *a*	0.41 (0.05) *c*	0.034 (0.04) *a*	0.036 (0.05) *c*	4.33 (6.99) *c*
Shallow Disk Injection	3	6.72 (10.42) *ab*	0.46 (0.41) *bc*	0.78 (0.09) *bc*	0.85 (0.16) *ab*	0.015 (0.017) *a*	0.053 (0.08) *cd*	63.9 (102) *bc*
Pressurized Injection	2	4.22 (2.04) *ab*	0.74 (0.13) *bc*	1.59 (0.27) *a*	0.72 (0.21) *ab*	0.030 (0.01) *a*	0.045 (0.04) *bc*	28.45 (6.02) *c*

† Depth was determined by normalizing runoff volume plot area

‡ Different letters within columns indicate significant differences between treatments using an analysis of variance and Tukey's mean seperation $p < 0.05$ for concentrations (mg L^{-1}) and non-parametric Freidman two-way analysis of variance by ranks and multiple comparison as described by Ipe (1987) for loads (kg ha^{-1}) $p < 0.10$

Broadcast manure without incorporation. Compared with other manure application methods, total P losses in runoff following broadcasting of manure were intermediate in 2006, when losses overall were low from all treatments, even though concentration of P in runoff were far higher than any of the other treatments. This reflects the low amounts of runoff water generated that year and large variability in depths between plots. In 2007, when runoff depths were considerably greater, broadcasting manure yielded the highest average total P loss of all treatments, although differences with the plowed and control treatments were not statistically significant due, again due to variability in runoff depths (Table 4). Indeed, average losses of total P from the broadcast treatment were five times higher than the control and six times higher than chisel plow treatments. The high losses associated with broadcasting manure reflect the WEP in manure on the soil surface which is a ready source of dissolved P in runoff. Even so, a substantial fraction of P loss from the broadcast treatment was associated with forms of P other than DRP, which accounted for 50-62% of total P. It is likely that particulate manure P, or manure "flocs" (light organic matter), was also removed by runoff water.

Manure incorporation by chisel plowing. Trends in total P losses in runoff following incorporation of broadcast manure with chisel plowing differed between years. For both years there was no statistical difference in total P loss between the broadcast and chisel plowing treatments, although mean losses were up to 84% lower for the tillage treatment. In 2006, when runoff depths were low, incorporation by tillage yielded significantly lower total P losses than pressure injection and shallow disk treatments (77% and 50% respectively), with only the banded aerator treatment having lower losses (Table 4). The opposite was observed in 2007, where all other methods of incorporating manure had significantly lower total P losses (> 62%) compared to incorporation with plowing.

Results of the chisel plowing treatment highlight the trade-offs in this method with regard to controlling particulate and dissolved forms of P loss in runoff. Incorporating broadcast manure by chisel plowing, lowered dissolved P losses in runoff with dissolved P representing only 2-4% of total P loss across both years. Tillage served to mix manure with soil, diluting WEP at the soil surface, hence limiting direct transfer of manure WEP to runoff water. In addition, eroded sediments in runoff water may have contributed to the sorption of dissolved P during the runoff event. However, particulate losses of P were undoubtedly exacerbated by tillage, as has been established elsewhere. Although particulate P was not directly measured in this study, it is likely that the majority of total P that was not in DRP form fell in that category. Thus, up to 98% of total P in runoff from the incorporation by chisel plowing was in particulate form.

Aeration and banded manure application. Total P losses from the aeration and banded manure application treatment were consistently the lowest of all treatments (Table 4). In fact, average total P losses in runoff from the banded aerator treatment over both years were < 4% of those observed from plots broadcast with manure. These low losses can be attributed to the effect of aeration on rainfall infiltration into the soil. Other authors have also documented reductions in runoff P losses with the use of aeration on well drained soils. For instance, in Georgia, aerating well-drained grassland soils reduced dissolved P loss and runoff volumes by 35%.

Although P losses from the banded aerator treatment were low, concentrations of P in runoff were amongst the highest in the study (Table 4). In 2007, dissolved P concentrations contributed to 64% of total P in runoff and were significantly higher than broadcasting manure followed by incorporation and the control. This reflects large amount of exposed manure and associated WEP. It is notable that these concentrations were only measured in runoff from a few plots; runoff was only generated from one of three replications in 2006 and two of three replications in 2007.

Shallow disk injector. Trends in total P losses associated with shallow disk injection were inconsistent between years. In 2006, total P losses were higher than all other treatments, including broadcasting manure, except the pressure injector, which had the highest losses. In 2007, total P losses were significantly lower than the broadcast manure treatment and even the control (Table 4). Results point to an important aspect of applicator performance. Even though the same shallow disk injection unit was used in both years of the study, the performance of the shallow disk injector appeared to have been affected by the use of different manure tankers with varying abilities to exert consistent hydraulic down pressure.

Pressurize injection (DGI). In 2006, losses of total P associated with pressure injection were among the highest of all treatments whereas in 2007 they were among the lowest. Concentrations of total P in runoff with pressure injection averaged 53-66% of runoff from broadcast manure plots, pointing to good removal of manure P from the soil surface with pressure injection. Relative trends in P loss with pressure injection were driven by runoff depths, which were greatest from this treatment in 2006 but among the lowest in 2007. The cause of this variability is unclear. It is notable that the pressure injector had a tendency to scrape crop residue from the soil surface and expose the soil to direct raindrop impact, although no increase in soil erosion was detected in comparison with other methods.

CORN PLANTING AND YIELDS

Corn was planted following all ammonia measurements and rainfall simulations. Consequently planting dates were generally much later than would be recommended for this location. In 2005 the plots were not planted until late June. In 2006 and 2007 they were planted at the end of May. This late planting severely limited the value of the agronomic crop response information due to the treatments. Plots were harvested for silage yield determination. Following that a cover crop was established. Yield results for the 2006-08 crop years are shown in Figure 11.

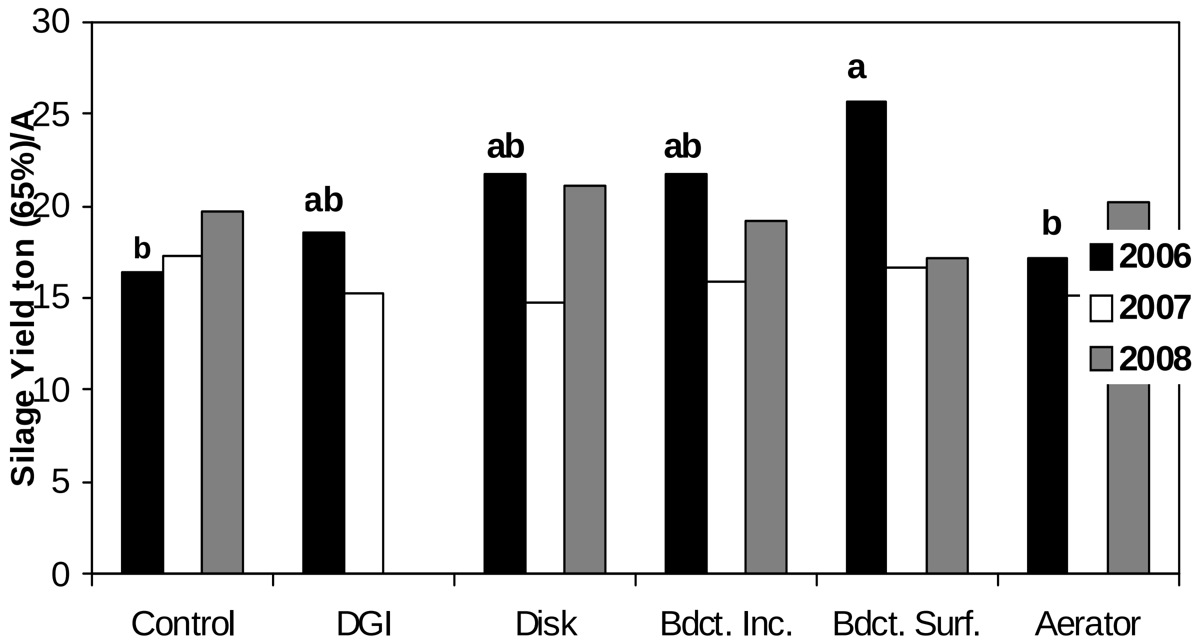


Figure 11. Silage yield (65% moisture) for the 2006-08growing seasons. Yields in 2006 with the same letter are not statistically different at the 0.05 level of significance. In 2007 and 2008 there were no statistically significant differences in yield.

In 2006 the yield from the broadcast treatment was statistically higher than the yield in the check and the aerator treatments. While it was not higher than the other treatments it is puzzling why this treatment yielded so well. This was not expected. The other injection treatments did yield numerically higher than the control, however these were not statistically different from each other or from the control. In 2007 there were no differences in yield between the treatments. As in 2007, there were no significant differences in yield due to the treatments in 2008. There was a very slight but insignificant trend favoring the shallow disk and aerator no-till applicators. Yields in this experiment have been lower than what is common in this area but every year planting has been delayed well beyond the optimum date because of the timing and time required to do all of the measurements and rainfall simulations before planting.

PRINCESS ANNE, MD FIELD SITE

The Princess Anne, MD site, located on the University of Maryland Eastern Shore (UMES) Research Farm, provided a strong contrast to the conditions found at the Rock Springs site. The site contains flat, coastal plain soils that are drained by ditches due to a high regional groundwater table, and leaching losses of nutrients are the primary concern. As with the Rock Springs site, six treatments were tested on field scale plots at the site, with 3 replications of each treatment spread across three blocks located along different contours. As with Rock Springs, in 2006 and 2007 dairy manure was applied, while in 2008 and 2009 swine slurry was used. Unlike Rock Springs, the aerator applicator was not tested at Princess Anne. Instead, we included an alternative broadcast treatment in which a P binding amendment (acid mine drainage residuum) was poured into the manure tanker prior to application. In addition, in 2008, we discontinued testing of the DGI and instead tested a novel chisel injector with “anti-leaching” sweeps intended to cut off macropore drainage of slurries (patent by DSI Ag). Details of the general layout of the UMES experimental site are displayed in Figures 12.

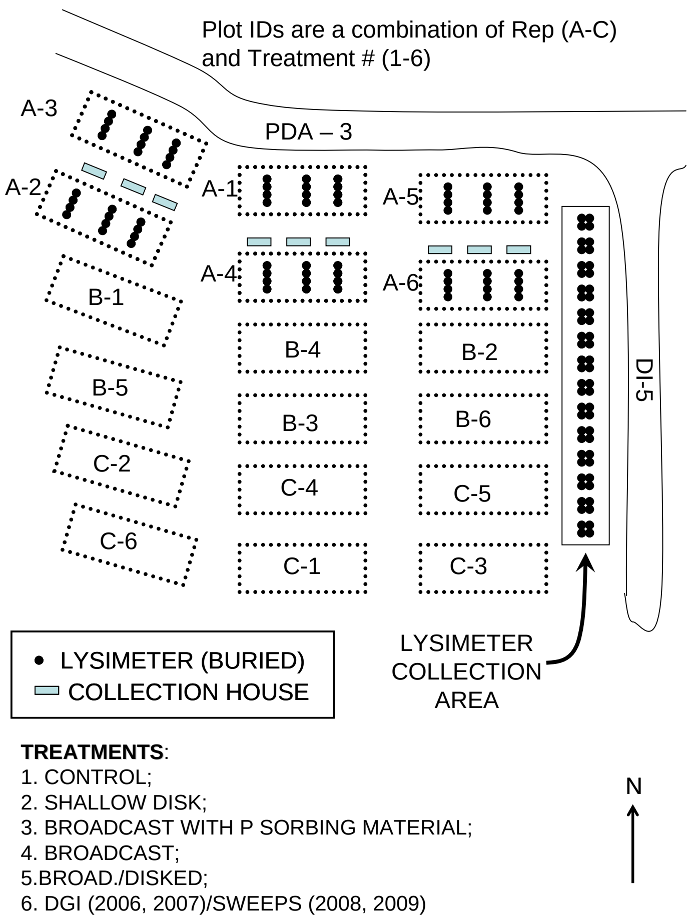


Figure 12. Layout of plots and groundwater monitoring lysimeters at the UMES Research Farm field site in Princess Anne, MD.

Relative trends in nutrient leaching losses differed when dairy manure (2006) and swine manure (2007, 2008) were applied, pointing to manure properties as important modifiers of applicator performance. In addition, large fluctuations in annual losses within individual treatments highlight the importance of climatic variability in water quality measurements.

While trends in total P leaching losses were somewhat variable (Figure 13), results revealed the potential for manure application methods to significantly limit P leaching on the Eastern Shore of Maryland, where subsurface transfers of P are the primary threat to the Chesapeake Bay. In 2006, when dairy manure was used, large differences in total P leaching losses were observed between the control and broadcast manure treatments, which had losses < 1 kg ha^{-1} and all other treatments. Since that year was the first year following lysimeter installation, it is possible that results were modified slightly by differential re-establishment of soil properties.

In 2007, leaching losses were low across the board for the first year of swine manure application, resulting in no significant trends related to application method. In 2008, however, loads averaged were higher than in previous years, reflecting extremely wet conditions and considerable leachate volumes. That year, loads of total P associated with shallow disk injection were significantly greater than all other loads, while the new “anti-leaching” chisel sweeps significantly lowered leaching losses of P, even below background levels. The 2008 results suggest that tillage below the injection furrow cuts off not only leaching of manure P along preferential flow pathways, but also soil P from the surface, where it is most concentrated. We await the results of 2009 to confirm these important findings, but have tested this further in laboratory settings and are confident that P leaching losses with manure injection can be significantly curtailed with small modifications to existing equipment..

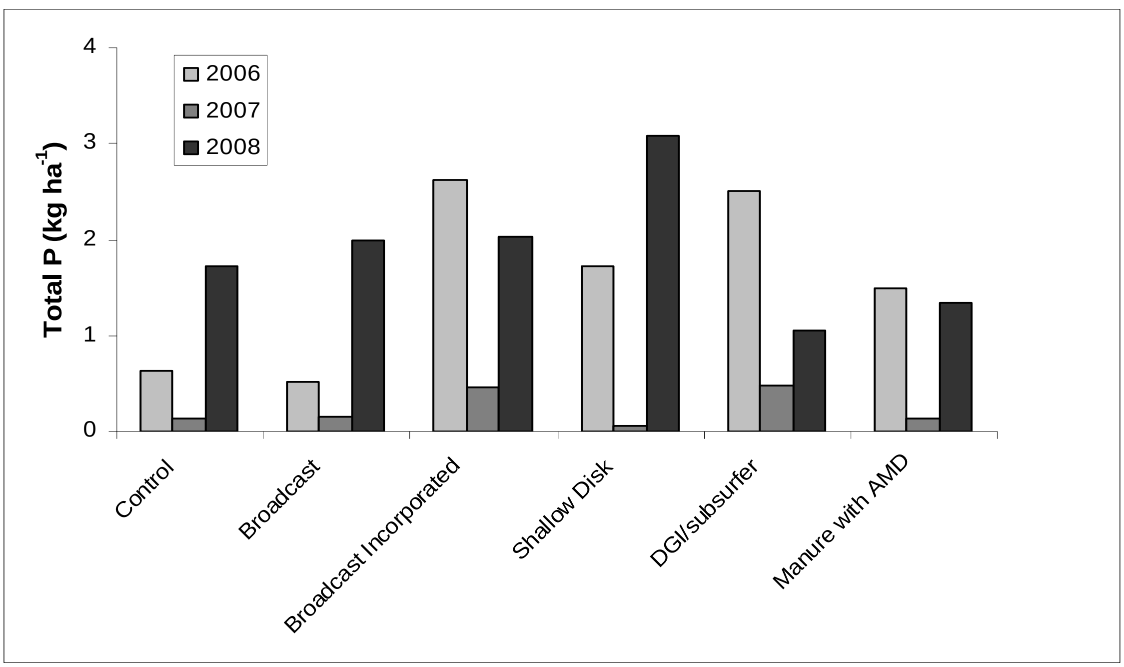


Figure 13. Total phosphorus loads (kg ha^{-1}) in leachate for the different low disturbance manure injectors at Princess Anne, MD.

Nitrate leaching losses in 2006, following dairy manure application (Figure 14), followed trends that were consistent with those observed with total P leaching losses that year. We expect that the equilibration of lysimeters was not as important to nitrate N transport that year as it may have been to total P, as nitrate travels via matrix flow (piston flow) whereas P travels primarily via macropore flow. In 2006, the control and broadcast manure treatments had the lowest losses, reflecting the absence of a manure N source in the control and the likely volatilization of ammonia from the broadcast treatment. Notably, the broadcast treatment with the P sorbing material was intermediate in nitrate losses to the control and broadcast treatments and the remaining treatments (DGI, shallow disk, incorporated by tillage). In 2007, nitrate leaching losses were low across all treatments and no significant differences were observed. In 2008, the control treatment and the broadcast treatment with P sorbing material had lower nitrate leaching losses than all other treatments. The lesser losses associated with the P sorbing material may have resulted from greater ammonia volatilization with this material, which has a high pH as it contains significant quantities of lime. However, it is unclear why a similar trend was not observed in 2006.

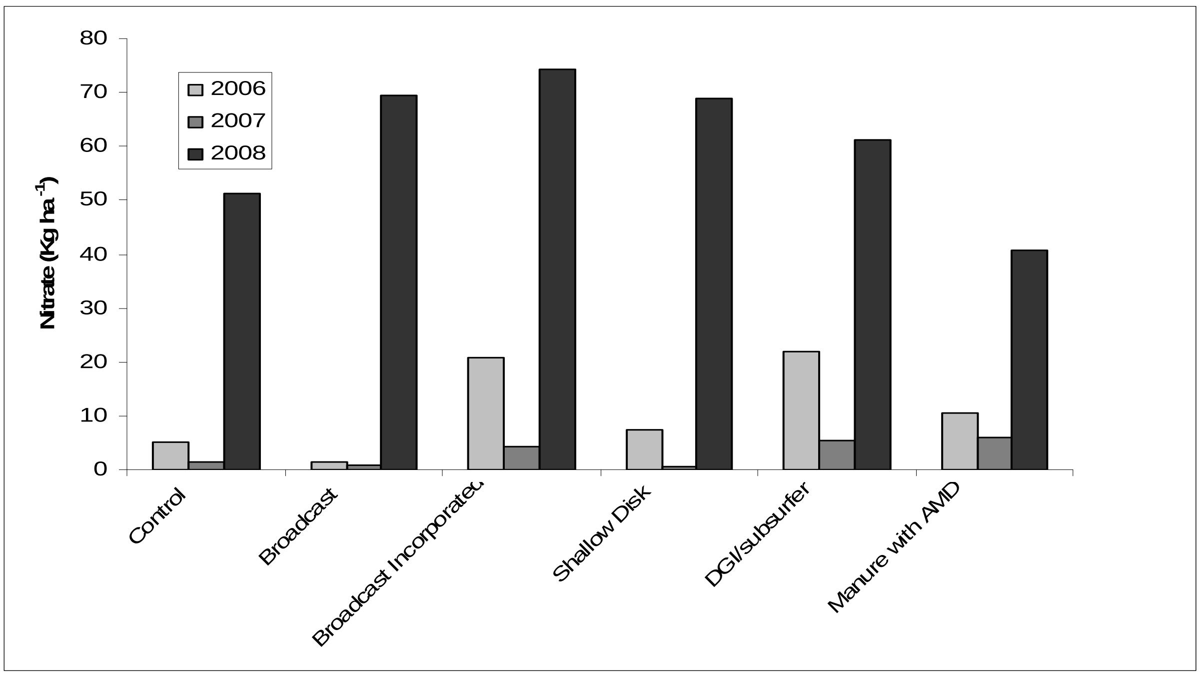


Figure 14. Nitrate nitrogen loads (kg ha^{-1}) in leachate for the different low disturbance manure injectors at Princess Anne, MD.

WHOLE FARM MODELING

Process-based, whole-farm simulation provides a tool for a comprehensive evaluation that considers the impacts and interactions of manure application on machinery use, fuel and labor requirements, crop yield and quality, feed production, and ultimately the overall economics of the farm. By simulating manure application strategies along with other important farm processes over many years of historical weather, major impacts and interactions can be explored and quantified. This type of analysis can be done using the Integrated Farm System Model, a software tool for simulating and comparing farm production systems developed by Rotz at the USDA-ARS Pasture Systems and Watershed Management Research Unit.

The farm simulation model was used to compare the five alternative manure application methods on a representative dairy farm in Pennsylvania. The Integrated Farm System Model was able to represent the corn silage production, water balance, volatile ammonia N loss, nitrate N leaching loss, and P runoff losses measured during the first year of the field plot trials with manure application treatments of no manure application, broadcast application without incorporation, broadcast application with tillage incorporation, band application with aeration, shallow disk injection, and high pressure injection. Measured and simulated results showed that incorporation of manure below the soil surface through tillage or injection reduced ammonia N losses but tended to increase nitrate leaching losses. Effects of the manure application strategy on P losses were less clear, but there was a trend toward less surface runoff loss of P with injection of manure and greater loss of sediment bound P when tillage was used to incorporate manure.

Whole-farm simulation of each of the manure application strategies on a dairy farm in central Pennsylvania indicated that reductions in ammonia N loss and runoff loss of P can be obtained with the use of shallow disk injection without adversely affecting farm profitability (Figure 15). Use of broadcast application with tillage incorporation, band application with aeration, or high pressure injection reduced average annual farm net return by $34, $22, and $30/cow, respectively compared to broadcast application of manure without incorporation. Additional benefits such as odor reduction may also be obtained, which may help justify the additional production cost even when no direct economic benefit is received.

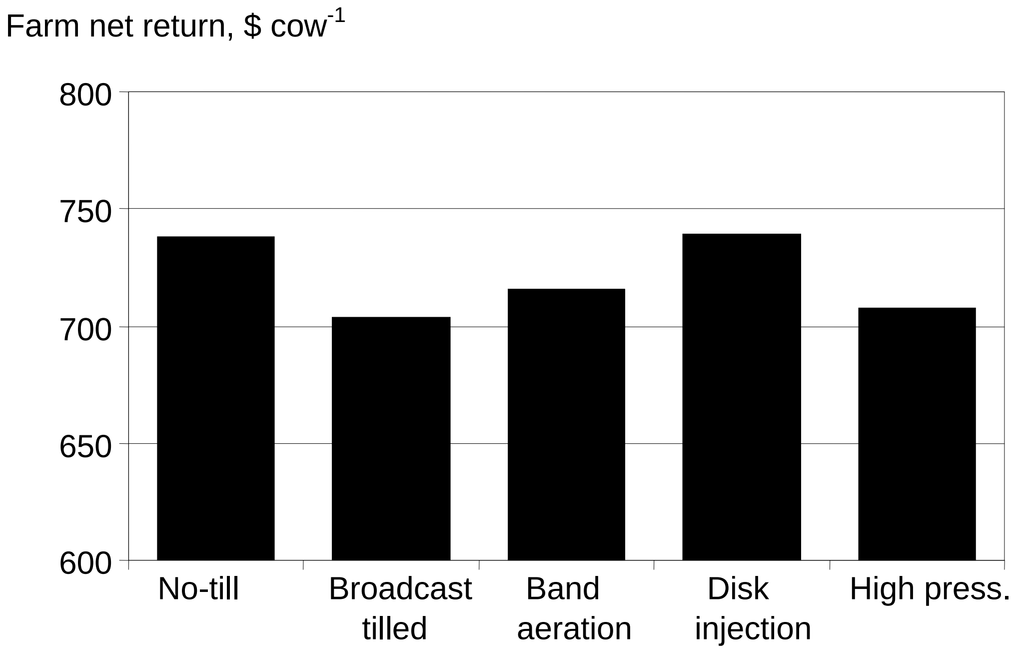


Figure 15. Net return of a 100-cow dairy farm in central Pennsylvania as influenced by the type of manure application method used.

SIGNIFICANCE OF FINDINGS AND RECOMMENDATIONS

Through this project we gained invaluable experience with the practical use of these application systems. A key finding is that each application system has its own unique attributes. This is very important to farmers and farm advisors who are looking at these systems for use in nutrient management plans. Currently because there is little research information available, these systems are often lumped together as generic low disturbance manure injectors and differences in performance are usually not considered. This research has shown that the potential user must evaluate specifically what they want to accomplish with the applicator. For example, in this research the aeration equipment set up to do minimal disturbance in a no-till system did an excellent job of reducing P loss but was not very effective at reducing N volatilization losses. Thus if reducing N volatilization losses and maintaining a no-till environment was a primary concern, this would not be a good choice . While this is only one location with one manure type, which would not be sufficient to change the Agronomy Guide N availability factors, we can make preliminary estimates of what the availability factors might be for manure N applied with these systems. This is critical information in developing a nutrient management plan that would include these systems.

Some specific findings are summarized in the following list:

- The shallow disk injector is the most consistent in terms of reducing environmental emissions of nutrients and odor relative to the worst case scenario of surface application. Additionally, a whole farm modeling analysis comparing these alternative manure injection systems in no-till showed that this injector was also the most profitable. Based on this one site and comparing these relative results to the N availability factors for dairy manure in the Agronomy Guide, the estimated N availability factor for dairy manure for this system would be very close to the 50% availability factor for immediately incorporated dairy manure. Also, as an interim recommendation we are suggesting that this be considered as incorporation for the manure application method in the current Pennsylvania P Index.
- The aeration infiltration device performed poorly with regard to nitrogen and odor emission but practically expunged phosphorus runoff and erosion. Based on this one site and comparing these relative results to the dairy manure N availability factors in the Agronomy Guide the estimated N availability factor for dairy manure for this system would be close to the 30% availability factor for dairy manure incorporated within 5-7 days. Also, as an interim recommendation we are suggesting that this be considered as incorporation for the manure application method in the current Pennsylvania P Index.
- The high pressure injection apparatus performed very well in conserving nitrogen and reducing odor but performed poorly with regard to phosphorus runoff. Unlike other application methods, it did not improve rainfall infiltration at the site and therefore was associated with high runoff volumes, hence high phosphorus runoff losses. This system has also presented practical problems with equipment reliability and problems with handling significant crop residues. Based on this one site and comparing these relative results to the dairy manure N availability factors in the Agronomy Guide, the estimated N availability factor for dairy manure for this system would be close to the 40% availability factor for dairy manure that is incorporated within 1-2 days.

The ultimate objective of this research was to provide information so that farmers, farm advisors, and nutrient management planners can evaluate the relative strengths and weaknesses of these different systems and make science based decisions on using these systems in their nutrient management plans. With the information derived from this research summarized above, a farmer can now make an informed decision about which system would best meet his requirements. These results also allow more accurate integration of these systems into nutrient management plans.

While conducting this experiment and demonstrating these systems under a variety of situations we also learned that the response to these systems will vary with the conditions. For example, this research was conducted with dairy manure. As noted above, the aeration system was not very effective at reducing N volatilization. Our observation was that this was because of the high fiber level in the dairy manure did not run down into the aeration holes very well, thus leaving a significant amount of manure on the surface. However, we demonstrated this equipment with swine manure and this very liquid, low fiber manure appeared to drain into the aeration holes very effectively. This would suggest that we will see a very different result with swine manure compared to dairy manure. One outcome of this research was that we were able to use this work as the basis for acquiring additional funding to repeat this work with swine manure. In another spinoff of this work, we have received funding to evaluate the aerator system in several different configurations such as applying the manure before aeration vs after and setting the applicator to do minimal disturbance or more vigorous disturbance. This will provide information for more refined management recommendations for use of the aerator system.

EVALUATION OF ACCOMPLISHMENTS TOWARD ACHIEVING OBJECTIVES

All objectives were accomplished

1) Evaluate the agronomic (N & P) and economic impact of several new alternative liquid manure application techniques in no-till crop production.

    Three years of data have been collected on the impact of several new alternative liquid manure application techniques in no-till crop production. The agronomic and economic strengths and weaknesses of these application systems have been quantified and evaluated.

2) Compare the effects of new and traditional liquid manure application methods on the fate of manure N and P in soil and loss in overland and subsurface flow; as well as quantifying N loss to the atmosphere in no-tillage crop production

    Three years of data have been collected on the impact of several new alternative liquid manure application techniques in no-till crop production. Impact data has included effects on reduction of ammonia volatilization loss, nitrate leaching loss, total P loss, soluble P loss, particulate P loss, and sediment loss.

3) Modify management recommendations and tools used by farmers to manage nutrients and conserve natural resources for profitable crop production and environmental protection.

    This project and the research site have been featured at a number of field days and other events since this project has begun. National and international visitors have toured the research site and discussed the methods and procedures with project scientists. A large number of farmers and farm advisors have attended educational programs and conferences where the results of this research have been used to educate these clientele on these alternative application methods. It is anticipated that these results will be used to modify the manure management tables in future editions of the Penn State Agronomy Guide and in revisions to the Pennsylvania Phosphorus Index.

OUTREACH AND SELECT PRESENTATIONS

The site at Rock Springs was featured on a number of field tours during the project, including Ag Progress Days which attracts over 50,000 people each year. The Rock Springs site was used for an NRCS training session, featured regularly in tours of Larson Agricultural Research Center at Rock Springs and served as as a teaching demonstration location for the Penn State College of Ag Nutrient Management course. An extension power point presentation based on the results has been prepared and has been and continues to be used at a number of professional and producer meetings in PA. Evaluation results from the project have been discussed at numerous extension meetings over the years. The site at UMES was featured on the tour for the SERA-17 (Organization to Minimize Phosphorus Losses from Agriculture) annual meeting, with attendees from across the US, Canada and Great Britain. Research results from the project have been presented at the American Society of Agronomy, Soil Science Society of America, Crop Science Society of America Annual Meetings over the past three years. This year, the project will serve as the centerpiece for a symposium developed by Kleinman and Beegle at the American Society of Agronomy meetings.

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Dell, Curtis J., John P. Schmidt, Peter J.A. Kleinman, Douglas B. Beegle, and Keisha Johnson. 200x. Ammonia and Nitrate Losses from Alternative Dairy Manure Application Methods. (Submitted for publication.)

Johnson, Keisha N., Peter J. A. Kleinman, Douglas Beegle, and Herschel Elliot. 200x. Effect of Manure Application Method on Phosphorus Loss in Surface Runoff. (Submitted for Publication)

PERSONNEL

Douglas B. Beegle, Professor, Department of Crop and Soil Sciences, Penn State University (Project PI)

Peter Kleinman, Soil Scientist, USDA ARS Pasture Systems and Watershed Management Research Unit, University Park, PA

Curtis Dell, Soil Scientist, USDA ARS Pasture Systems and Watershed Management Research Unit, University Park, PA

John Schmidt, Soil Scientist, USDA ARS Pasture Systems and Watershed Management Research Unit, University Park, PA

Alan Rotz, Agricultural Engineer, USDA ARS Pasture Systems and Watershed Management Research Unit, University Park, PA

Lou Saporito, Soil Scientist, USDA ARS Pasture Systems and Watershed Management Research Unit, University Park, PA

Michael Reiner, Hydrologic Technician USDA ARS Pasture Systems and Watershed Management Research Unit, Klingerstown, PA

Randy Bowersox, Research Support Technician, Department of Crop and Soil Sciences, Penn State University (Position partially supported by this project)

Justin Dillon, Research Support Associate, Department of Crop and Soil Sciences, Penn State University (Position partially supported by this project)

Tyson Myers, Technician, Department of Crop and Soil Sciences, Penn State University (Position partially supported by this project)

Arthur Allen, Professor, Department Agriculture, University Maryland Eastern Shore

Don Mahan, Field Manager, Department Agriculture, University Maryland Eastern Shore

Janice Donahoe, Laboratory Manager, Department Agriculture, University Maryland Eastern Shore

Keisha Johnson, Graduate Student, Department of Crop and Soil Sciences, Penn State University