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DEPARTMENT OF PLANT SCIENCE

# A COMPARISON OF INJECTED AND BROADCAST DAIRY MANURE IN AN ORCHARDGRASS HAY SYSTEM

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## ABSTRACT

Injecting manure has been suggested for use in perennial grassland systems as a method to conserve nitrogen and increase yields. The objective of this study was to compare the impacts of open-slot injected versus surface-applied liquid dairy (*Bos Taurus*) manure on yield, nitrous oxide ($N_2O$) emissions, ammonia ($NH_3$) emissions, and nitrogen and phosphorus runoff losses in an orchardgrass (*Dactylis glomerata*) hay system. This study consisted of six replicates with two manure application treatments (open-slot injection and surface-applied) as well as one control managed with synthetic fertilizers. Manure was applied 3 times during each growing season with four harvests in each of the three experimental years (2015, 2016, and 2017). Dry matter (DM) yields were significantly different between manure treatments only in 2015, and significant difference ($p=0.05$) was observed between injected and control plots in 2017 with the higher yield in the injected plots in both circumstances. Cumulative $N_2O$ emissions were greater in the injected plots than in surface-applied or control for nearly all applications for the extent of the study. Conversely, average $NH_3$ volatilization emissions were significantly larger in the surface-applied plots than in the injected or control plots. Conservation of nitrogen as $NH_4^+$ in the soil resulted in a reduction of volatilization loss by about 50% in injected plots. No significant difference was observed between manure treatments in the amount of nitrogen or phosphorus lost in runoff water. Nutrients lost in runoff were instead the product of the rate and volume of the precipitation event and resulting amount of infiltration excess. These results indicate that nitrogen is conserved through an open-slot injection application. However, factors other than nitrogen availability may have limited orchardgrass growth in this system, causing mixed results in yield response.

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# Chapter 1

## Introduction

In the region of the United States that is contained within the Chesapeake Bay Watershed, there is increasing scrutiny around manure application practices. Historically, manure was surface applied, or broadcast. However, this application method is often associated with higher losses of nitrogen and phosphorus to the environment. Tillage was the most common method used to incorporate manure materials into the soil, but that practice is inconsistent with perennial forage production. One practice that has been recommended for perennial forage lands is the incorporation of manure through the process of injection (Maguire, et al., 2011). A large number of studies have investigated the utility of manure injection in corn crops. However, liquid manure injection can have utility in perennial grass hay systems as well.

Immediately following the land application of manure, the process of volatilization of ammonia is the most significant loss pathway for manure nitrogen (Dell, et al., 2012). The majority of ammonia emissions is expected to occur during the first 24 hours following a field application of manure (Duncan, et al., 2017).

Loss of nitrogen as ammonia is of great environmental concern. In the atmosphere, concentrations of ammonia can lead to the formation of fine particulate matter. Fine particulate matter can reduce visibility by causing a haze and can also pose a hazard to human health. Fine particulate matter is small enough to be absorbed through the lungs and into the bloodstream following inhalation (USEPA, 1997). In addition, ammonia can be carried great distances with the wind. As a result, ammonia can be deposited and cause degradation of environmentally sensitive areas (Sutton, et al., 1998). In bodies of water, like the Chesapeake Bay, ammonia deposition can contribute to eutrophication.

Loss of ammonia from soil is also an agronomic concern. Manure is generally applied to farm fields as a way to reduce the cost associated with the application of commercial nitrogen fertilizer and to utilize a waste material produced on livestock operations. Under broadcast application of manure, 30-70% of the ammonium nitrogen contained in the manure is typically lost to volatilization (Thompson and Meisinger, 2002). The practice of injecting manure can reduce ammonia emissions by greater than 90% (Duncan, et al., 2017; Dell, et al., 2012). The reduction of ammonia loss is related to an increase in the amount of plant-available nitrogen that remains in the soil. The conservation of the ammonia nitrogen makes the use of the manure more efficient in that more pounds of nitrogen are available to the plants per pound of manure applied. In studies involving manure injection in corn systems, the efficiency could be measured either by a comparison of the yield at the end of the growing season, or by a comparison of a pre-sidedress soil nitrate test. When manure is injected before corn planting, an increase in the crop uptake of the nitrogen applied in manure is observed. As a result, there is opportunity for an increase in yield associated with manure injection, though the increase may not always be observed (Dell, et al., 2012; Myers, et al., 2013; Duncan, et al. 2017).

There has been a very limited number of studies involving manure injection in grasslands. They have been somewhat less conclusive in the area of nitrogen efficiency as it relates to hay or pasture yield. While nitrogen is still considered to be the main limiting nutrient in grass based hay systems, studies have noted equivalent to decreased yields on sites with manure slurry injection (Louro, et al., 2016; Rodhe, et al., 2006; Sadeghpour, et al., 2018). However, the amount of nitrogen available to the crops is increased under injection management

(Huijsmans, et al., 2016). The lack of yield increase with an increase in available nitrogen could be due to the presence of organic nitrogen in the soil that is readily mineralized for the hay crop. The nitrogen provided by mineralization could be meeting the crop requirement, and the extra nitrogen conserved by injection is in excess of the amount the crop is able to utilize. The lack of yield increase could also have been the result a number of factors unrelated to nitrogen availability including injury to the sod caused by the injection equipment, water availability, or soil compaction (Rodhe, 2006).

Nitrous oxide is another form through which nitrogen can be lost to the atmosphere. Nitrous oxide is an extremely potent GHG with a 100-year global warming potential approximately 298 times that of carbon dioxide (Myhre, et al. 2013). As a result, this pathway of loss is of great environmental concern.

In a study conducted in central Pennsylvania, Duncan, et al. (2017) collected gas from closed chambers above the soil surface in order to analyze it for nitrous oxide emissions. In all plots, there was a peak in emissions approximately 7 to 10 days after manure application. During one year of the study (2011) nitrous oxide emissions were greatly reduced in all plots, presumably in response to the lack of rain throughout that growing season. This study found that there was a significant increase in the rate of $N_2O$ emissions in the injected plots versus the broadcast plots. Duncan, et al. (2017) indicated that the rate of $N_2O$ emissions remained relatively stable across the broadcast treatments throughout the growing season at a rate less than 100 g $N_2O$/ha/day. The injected treatment showed a peak approximately 10 days after manure applications at a rate of approximately 400 g $N_2O$/ha/day.

Sadeghpour et al. (2018) measured nitrous oxide emissions in alfalfa (*Medicago sativa*) and tall fescue (*Festuca arundinaceae*) systems following broadcast and injected manure applications. These researchers measured $N_2O$ emissions through the same method as Duncan et al. (2017). Sadeghpour et al. (2018) discovered that emissions of $N_2O$ were increased with injection in only one of two study years. They suggest that the different results in treatment years could be due to a change in the weather and soil conditions. Soil moisture was greater in the second year of the study than the first, and this observation correlated with the greater $N_2O$ emissions in the second year.

Markfoged et al. (2011) utilized a different approach in the measurement of $N_2O$ emissions. This study looks specifically at the mechanisms that cause the emission of $N_2O$ from the soil. While the other experiments utilized field-scale equipment to study the emissions, these researchers designed an apparatus that would apply a very precise amount of manure in a very narrow band within the soil. They then took a core of soil 3 cm in diameter and analyzed that core for oxygen concentration around the band. Prior to manure application, the soil profile showed consistent $O_2$ concentration throughout all depths. Following manure injection, the section of the profile impacted by the manure band showed an area that was depleted of oxygen. These findings are consistent with the field scale trial conducted by Duncan et al (2017). Markfoged et al. (2011) suggest that the increase in $N_2O$ emissions is due to the creation of an anaerobic microclimate adjacent to the manure. This anaerobic microclimate causes facultative aerobic soil microorganisms to utilize nitrate as an oxygen source in the absence of oxygen. It can also be inferred that there is a greater amount of nitrogen in the soil as a result of the decrease in ammonia emissions. This greater amount of nitrogen can contribute more to the loss as $N_2O$.

In addition to the loss of gaseous forms of nitrogen, phosphorus lost from the site of manure application can also cause a threat to the environment. Elevated levels of phosphorus in freshwater is the leading cause of eutrophication (Correll, 1998). The amount of dissolved reactive phosphorus in runoff water is greater when manure is broadcast on the surface in comparison to when it can be incorporated (Johnson, et al., 2011; Schuster, et al., 2017). The magnitude of decrease in phosphorus content in injected treatments is much greater at high runoff flow rates (Schuster, et al., 2017). For manure applied right before a significant rainstorm, injecting manure conserves more phosphorus in the soil profile while contributing less to the pollution of the runoff water.

A large number of studies have been conducted on the utility of manure injection in corn fields. However, there are few studies that investigate the impacts this method of manure application can have in perennial hay crops. The purpose of this study is to investigate the differences in ammonia volatilization, nitrous oxide emission, phosphorus runoff, and forage yield between injected and broadcast applied dairy slurry in an orchardgrass hay system. We hypothesized that there would be a decrease in phosphorus content in runoff water, a decrease in ammonia volatilization, and an increase in nitrous oxide emission in the injected manure plots. Additionally, we predicted an increase in yield in the injected manure plots due to the conservation of plant-available nitrogen.

# Chapter 2

# Materials and Methods

## Site Description

The field study was conducted at the Pennsylvania State University Russell E. Larson Agricultural Research Center in Rock Springs, Pennsylvania. The site was 1.4 hectares in size and managed as an orchardgrass (*Dactylis glomerata*) hayfield for the duration of the study. The orchardgrass at the site was planted on August 20$^{th}$, 2013, with treatments beginning in 2015. Throughout 2014, the grass in all plots received ammonium sulfate fertilizer to promote stand establishment. Prior to the experiment, corn was grown at the site with a history of a dairy (*Bos taurus*) and swine (*Sus scrofa*) manure application study (Johnson et al. 2011). The site consisted of well-drained Hagerstown silt loam (fine, mixed, semiactive, mesic Typic Hapludalf) soil with an average slope of 3-8%. Prior to the start of the study, the average soil pH was 5.74 in the top 5 cm of the soil, and was 5.62 in the depth of 5-15 cm. In addition, the average Mehlich-3 phosphorus was measured to be 24 ppm in the top 5 cm, and 29 ppm in the depth of 5-15 cm. The average Mehlich-3 potassium concentration was measured to be 44 ppm in the top 5 cm, and 48 ppm in the depth of 5-15 cm. According to the NRCS SCAN measurements, total precipitation on the site for each water year (October 1 of previous fall to September 30 of current year) was 94.41 cm in 2015, 86.31 cm in 2016, and 194.46 cm in 2017. Data for September 2016 was not available from NRCS SCAN, so it was substituted with precipitation measurements from a USDA ARS station approximately a quarter mile from the site. 2015 and

2016 precipitation values were both slightly less than the average Pennsylvania precipitation, while 2017 was wetter than average.

The site consisted of 18 plots with dimensions of 10m x 12m. The project consisted of six randomized blocks, each consisting of three plots. This study tested two methods of manure application, with the use of commercial nitrogen, phosphorus, and potassium fertilizer in the control plots. Figure 1 illustrates the layout of treatments and blocks at the research site.

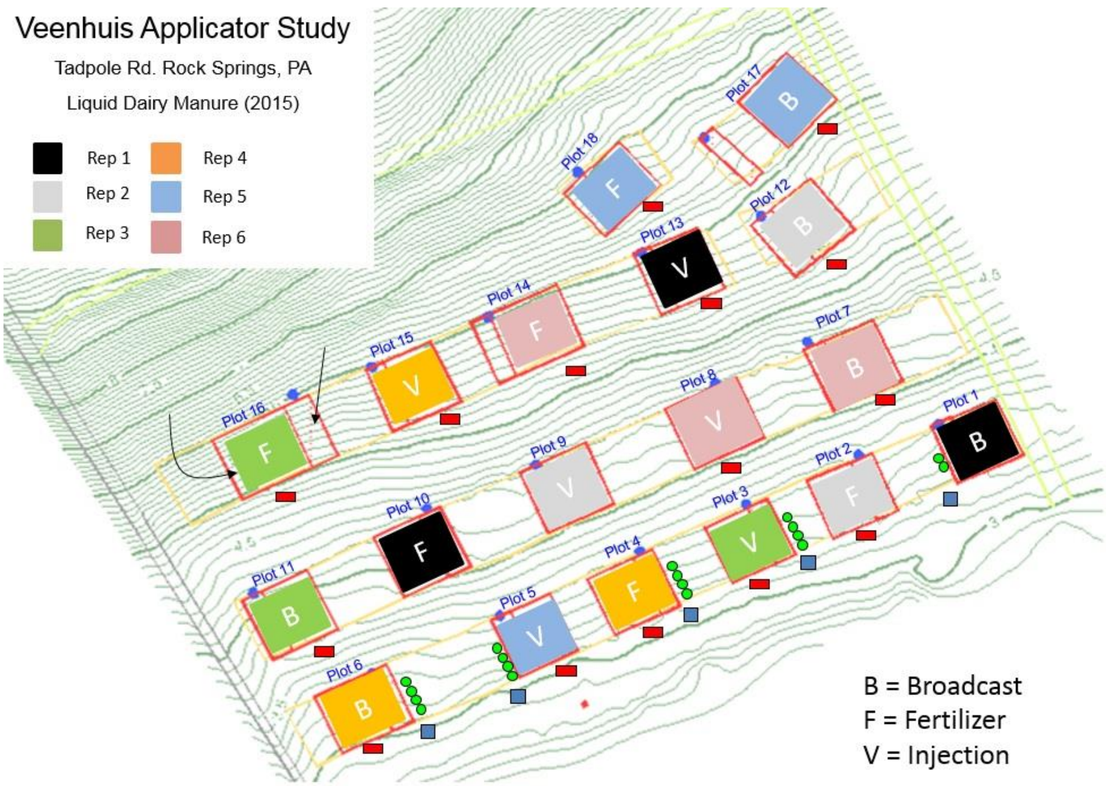


**Figure 1. Map of experimental blocks and treatments at Rock Springs research site**

## Manure Application

Liquid dairy manure was applied at a rate of 42.7 Mg/ha to both broadcast and injected treatments. Manure for this study was provided by a neighboring dairy farm, and analysis of the manure was taken at each application date. Manure samples were analyzed at the Penn State Agriculture Analytical Services Laboratory in University Park, Pennsylvania. A Veenhuis

Euroject open-slot disk manure injector from Veenhuis Machines B.V. (Raalte, Overijssel, the Netherlands) was used for both broadcast and injected treatments. The injector was approximately 3m wide, and it was driven for 4 passes through each plot to obtain the plot width of 12m. Table 1 describes the contents of the manure applied at each treatment date. Manure composition information was not available for the 12-Sep, 2017 application date. Fertilizer was applied to plots on the same day as manure. Manure and fertilizer were applied between mid-morning and early afternoon at each treatment date.

*Injection (Veenhuis)*

The injection equipment on the Veenhuis machine was inserted into the soil in this treatment. The knives on the unit cut a slit into the soil profile and manure was injected into the slot, approximately 5-8 cm into the soil profile. With this application method, the slit remains open after application. Following application, a small amount of manure is visible on the surface of the soil.

*Broadcast*

The injection equipment on the Veenhuis machine was not inserted into the soil for this treatment. Instead, manure was allowed to drop from the hoses on the back of the unit and lay on top of the soil surface. As a result, the manure covered most of the surface area of the soil immediately following application.

*Control*

This treatment received no manure. Instead, mineral nitrogen, phosphorus, and potassium were applied to meet nutrient demands of the crop. In 2015, urea (46-0-0) was applied at a rate of 186 kg/ha on each treatment date. In 2016 and 2017, ammonium sulfate (21-0-0) at a rate of 408 kg/ha was applied at each treatment date. In addition, 224 kg/ha of 0-25-25 was applied once in

2016 (25-May) and once in 2017 (6-June) to supply phosphorus and potassium to the orchardgrass crop.

**Table 1. Manure application dates and nutrient composition (nutrient contents reported on a wet weight basis)**

| Date | Total Solids (%) | Total N (kg/Mg) | $NH_4$-N (kg/Mg) | Total N Applied (kg N/ha) | Total $P_2O_5$ (kg/Mg) |
|---|---|---|---|---|---|
| **2015** | | | | | |
| 27- Apr | 8.6 | 3.53 | 1.62 | 150.73 | 1.32 |
| 28-May | 9.3 | 4.02 | 1.65 | 171.65 | 1.19 |
| 14-Aug | 6.3 | 3.10 | 1.43 | 132.37 | 1.63 |
| **2016** | | | | | |
| 15-Apr | 9.7 | 4.03 | 2.02 | 172.08 | 1.16 |
| 25-May | 10.4 | 3.8 | 1.53 | 162.26 | 1.24 |
| 25-Aug | 10.2 | 3.45 | 1.55 | 147.32 | 1.13 |
| **2017** | | | | | |
| 27-Apr | 10.61 | 5.73 | 1.92 | 244.67 | 1.29 |
| 6-Jun | 8.5 | 3.42 | 1.52 | 146.03 | 1.02 |
| 12-Sep | N/A | N/A | N/A | N/A | N/A |

Analysis data was not available for manure application on September 12, 2017.

Manure was applied approximately 1 month before the first harvest of the year, and at 2-5 days after the first and third harvests of the year.

**Orchardgrass Harvest**

Plant biomass harvests were taken at 4 points each growing season (2015: May-24, Jun-29, Aug-10, and Oct-05, 2016: May-23, Jun-28, Aug-22, and Oct-17, 2017: May-30, Jul-18, Sep-7, and Nov-20). Yield samples were collected with a Hege Plot Forage Harvester from Wintersteiger Seedmech (Ried im Innkreis, Austria). The harvest area was 1.5 m by 6 m. Wet weights were collected at harvest, and a smaller subsample was collected for dry matter measurements. Following the harvest of the sample, field scale haymaking equipment was used to mow, ted, rake and bale the material so that it was removed from the field as it would be in a production setting.

In the lab, the subsamples were dried at a temperature of 55 C in order to determine dry matter (DM) content. Once dry, samples were ground for further plant content analysis. Results are reported in kg DM/ha.

**Runoff**

Runoff was collected from 12 of the 18 plots, representing 4 of six experimental blocks. A berm is formed at each plot to direct the runoff water toward the base. At the base of each plot, a 6m long PVC pipe with open slits collects runoff water. Runoff water from the plot was transported through this pipe and collected in a small house near the plot. Runoff volume from each plot was calculated based on collection from a tipper system. For each plot, a small cup collected the runoff. When the cup was full, it tipped over and a small subsample of the runoff water was collected for laboratory analysis. Throughout the duration of the study, the number of tips for each plot was recorded in order to calculate the total volume of runoff collected in each plot.

The subsamples for each plot were collected after a major runoff event, such as large rainstorm or snowmelt. They were taken to the laboratory for analysis for concentrations of phosphorus and nitrogen. Samples were filtered, and both filtered (0.45 µm) and unfiltered runoff samples were utilized in analysis. Total dissolved P was determined with filtered samples. Unfiltered samples used to determine total P were digested with aqua regia following EPA standard method 200.2 (USEPA, 1994). Both filtered and aqua regia digests were analyzed by ICP-OES.

Total nitrogen was determined by alkaline persulfate digestion following the method of Patton and Kryskalla (2003).  Filtered (0.45 µm) and unfiltered samples were utilized to estimate both dissolved nitrogen and total nitrogen. Unfiltered samples measured total nitrogen ($NO_3^-$ and

$NH_4^+$). Filtered samples measured dissolved nitrogen ($NO_3^-$ and $NH_4^+$). Additionally, filtered samples were analyzed for $NO_3$-N using a flow-injection analyzer (Quick Chem FIA + 800 Series, Lachat Instruments, Loveland, Colorado).

**Nitrous Oxide**

*2015 and 2016*

Nitrous oxide emission measurements were taken at 3 to 4 day intervals for approximately 30 days following manure application. Nitrous oxide samples were collected following the protocol used by Dell et al., 2014. Vented gas measurement chamber with dimensions of 30 by 50 by 10 cm were constructed from stainless steel cafeteria serving pans (Vollrath Corporation). The chambers had a port through which gas samples could be collected with a needle and syringe. The chambers were attached to a base of the same area driven approximately 5 cm into the soil profile with two large binder clips. A foam strip at the base of the chamber allowed for an airtight seal. In 2015 and 2016, samples were collected 0 (ambient), 10, 20, and 30 minutes after the attachment of the chamber to the base. Samples were extracted from the chambers with 30 mL syringes and inserted into evacuated glass tubes. In this sampling method, samples were collected from all 18 plots at each sampling date. The samples were returned to the lab for analysis of nitrous oxide concentration with a Varian 3800 gas chromatograph. $N_2O$ flux rate was determined by a linear regression of gas concentration versus chamber deployment time.

*2017*

In 2017, a Gasmet DX4040 portable FTIR (Fourier-transform infrared spectroscopy) Gas Analyzer was utilized for nitrous oxide measurements. The analyzer was connected directly to a chamber of the same design as used in 2015 and 2016. The Gasmet analyzer measured $N_2O$ concentrations while deployed in the field at 30 second intervals for a period of 5-8 minutes for each plot. Exhaust air for the analyzer was returned to the chamber to minimize changes in air pressure or gas concentration within the chamber. $N_2O$ flux rate was also determined by a linear regression of gas concentration versus chamber deployment time with this sampling method. The use of the portable analyzer allowed for the collection of additional data points at each sampling date in the determination of flux rate.

This method of data collection was more time consuming in the field, so data was only collected for 12 of the 18 plots with the portable analyzer. Sample collection included 4 replicates of each treatment.

In all three treatment years, cumulative $N_2O$ emissions were calculated by determining the area under the plot of emission rate versus time with SigmaPlot Version 11 (Systar Software). In this method, it is assumed that the emission rate remained constant between sampling dates. As a result, changes in $N_2O$ flux rate are not accounted for between sampling dates. However, this measurement is a valuable tool to use in comparing treatments as each plot was sampled on the same date.

**Ammonia**

Ammonia emissions were collected for approximately 96 hours following manure application using the Semi-Open Chamber Method described extensively in the work of Shigaki and Dell (2015). Chambers were constructed with a 2-liter bottle and contained a sponge dipped into a container holding a pre-measured amount of acid. Within 1 hour of manure application, ammonia collection chambers were deployed. The sponge and acid trap were replaced throughout the collection period, with more rapid replacement in the first day. A total of 5 acid traps were deployed in each chamber at each sampling window. The sponges and traps were returned to the laboratory for analysis. A blank canister was analyzed with the samples collected from the field to allow results to be calibrated for detectable background levels of ammonium. The measurement of ammonia collected was adjusted with the assumption that sample collection and analysis accounted for 80% of ammonia emissions, based on the work of Jantalia et al (2012). Results reported are the sum of the five collection periods for each chamber.

**Statistical Analysis**

Yield, cumulative $N_2O$ emissions, ammonia volatilization, and runoff data were analyzed using a PROC GLM in SAS. $N_2O$ emission measurements on individual sampling dates were not normally distributed, so they were $log_{10}$ transformed and analyzed with a PROC MIXED model in SAS with treatments as fixed effects and blocks as random. Due to variation in weather, results are analyzed on an annual and by harvest basis. Tukey test was used to determine significant difference between means. Results are considered significantly different at $p=0.05$.

# Chapter 3

# Results and Discussion

## Orchardgrass Yield

Yields between treatments were significantly different on an annual basis in 2015 and 2017. In 2015, the average yield for injected plots was 20% larger than the average yield for surface-applied (broadcast) plots (Figure 2). The average yield for the control plot was not significantly different from either the injected or surface applied plots. In 2017, the average yield in the injected plots was 12% greater than the average yield in control plots. No significant difference was observed between the surface-applied plots and either the injected or control plots. In 2016, there was no significant difference observed between any of the treatments. Through June and July of 2016, the site experienced a severe drought. It is likely that the yields in that study year were limited instead by water availability at the site rather than an effect of the nutrients in the treatments.

When all three study years were pooled, the average yield for the injected plots (9975.7 kg/ha) was 10% larger than the average yield in surface-applied manure plots (9099.0 kg/ha) and 12% larger than the average yield in the control plots (8880.8 kg/ha). The difference in average surface-applied yield and average control yield was not significant. Figure 2 illustrates the comparison between the average yields for each treatment by growing season.

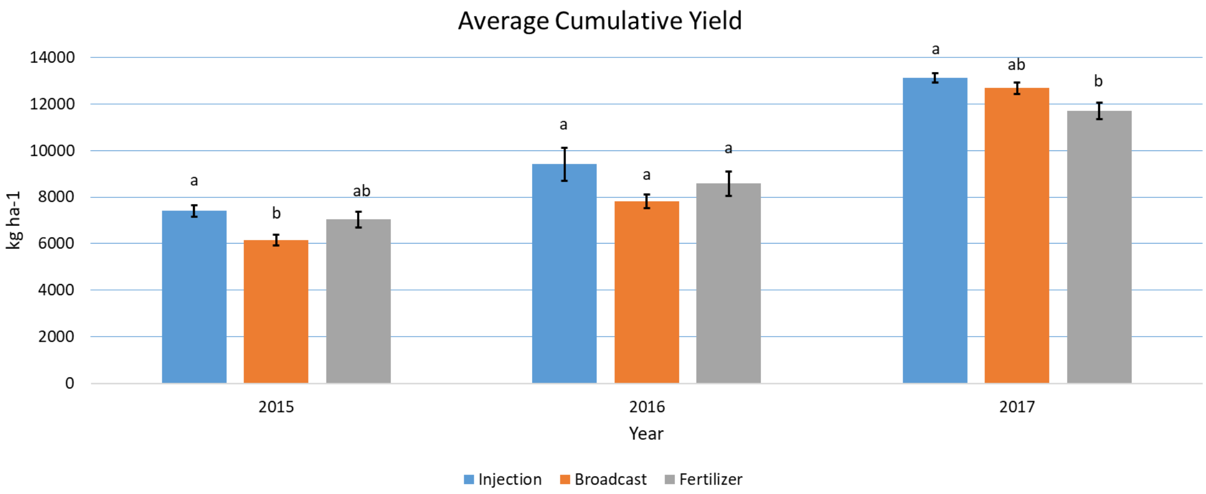


**Figure 2. Average cumulative yield by year and treatment**

It is also possible that the application of manure resulted in an increase in nitrogen available to the orchardgrass as the study progressed. When manure is applied, the ammonium fraction is immediately available to plants. However, approximately 50% of the nitrogen in manure is contained in the organic fraction. This fraction becomes available to the crop slowly throughout the season, and some is not available to plants until 2-3 growing seasons after application. As a result, some organic nitrogen was likely available to plots that had received manure that was not available in the control plots. This small but cumulative amount of organic nitrogen could have contributed to the observed difference in yields in 2017. In addition to the availability of organic nitrogen, the application of manure may have also led to an increase in the amount organic matter in the soil, and ultimately increased the water holding capacity of the soil. The increased water holding capacity could have provided additional plant available water to the manured treatments in later years in the study.

Between years in this study, there was a large difference in yields between study years. The difference in yield is likely due to a response to the weather. In 2016, there was a long period of drought through the summer. This lack of rain likely limited the yield of the crop.

Conversely, the 2017 growing season exhibited ample precipitation and soil moisture. As a result, yields were much higher in 2017 than in 2016, as illustrated in Figure 2.

The inconsistency of the yield pattern throughout the years of the study indicates that it is likely that orchardgrass growth was not limited strictly by nitrogen availability for each harvest interval. Instead, factors like moisture availability and temperature may have had a significant impact on the growth of the forage. However, a general trend in higher yields in the injected plots indicates a small advantage of that treatment.

**Ammonia Emissions**

Ammonia emission measurements were collected for five out of nine manure application dates. Table 2 indicates the differences in ammonia loss in both total amount, and as a percentage of the total amount of $NH_4$-N applied.

**Table 2. Ammonia loss as a proportion of ammoniacal N applied**

| Application Date | | $NH_4$-N applied (kg ha$^{-1}$) | $NH_3$ loss (kg ha$^{-1}$) | %-$NH_4$-N loss |
|---|---|---|---|---|
| | | *2016* | | |
| 25-May: | Injection | 65.33 | $3.29_b$ | 5.0 |
| | Broadcast | 65.33 | $7.03_a$ | 10.8 |
| | Fertilizer | 85.74 | $0.91_c$ | 1.1 |
| 25-Aug: | Injection | 66.19 | $1.78_b$ | 2.7 |
| | Broadcast | 66.19 | $3.70_a$ | 5.6 |
| | Fertilizer | 85.74 | $0.68_c$ | 0.8 |
| | | *2017* | | |
| 27-Apr: | Injection | 81.98 | $0.86_b$ | 1.0 |
| | Broadcast | 81.98 | $3.40_a$ | 4.1 |
| | Fertilizer | 85.74 | $0.46_b$ | 0.5 |
| 6-Jun: | Injection | 64.90 | $6.23_a$ | 9.6 |
| | Broadcast | 64.90 | $6.64_a$ | 10.2 |
| | Fertilizer | 85.74 | $5.79_a$ | 6.8 |
| 12-Sep: | Injection | -$^+$ | $0.66_b$ | -$^+$ |
| | Broadcast | -$^+$ | $2.11_a$ | -$^+$ |
| | Fertilizer | 85.74 | $0.79_b$ | 0.9 |

*$_{a,b,c}$ subscript denotes significant difference at application date.
$^+$Manure analysis data not available for this treatment date

On most treatment dates, losses of nitrogen as $NH_3$ were reduced by greater than 50% in the injection plots as compared to the surface-application plots. However, the emissions in the surface-application plots (4.1-10.8%) were much lower than the anticipated 30-70% loss based on manure application studies in corn (Duncan et al., 2017; Dell et al., 2012). There is a possibility that there was a problem with the recovery of ammonia with the Semi-Open Chamber Method. It is also possible that the perennial grass cover reduced the amount of $NH_3$ that escaped the field and entered the atmosphere. Manure was applied within two to three days of harvest, so the cover was no more than 6 inches tall at the time of application. However, even this small amount of cover can trap some $NH_3$ and keep it in the field.

However, the emission pattern was extremely different on 6-June, 2017. The volatilization measurements were greater than average in all three treatments. It is possible that this is due to a flaw in the collection method.

Ammonia emissions are closely related to a conservation of nitrogen from manure applications. Volatilization loss is the most significant form of nitrogen loss from fields receiving manure (Dell et al, 2012). The 50% reduction in ammonia loss observed in this study relates to a conservation of that nitrogen in the soil, and its potential for availability to the crop.

**Nitrous Oxide Emissions**

Measured flux rates of $N_2O$ are illustrated in Figure 3. Elevated emissions (flux rates) occur shortly after manure application. In the period of time between observations of elevated flux rates, $N_2O$ emissions were generally low. In the earliest manure application in spring, elevated flux rates typically occurred 7-10 days after manure application, consistent with findings from Sadeghpour et al. (2018) and Duncan et al. (2017). In the two manure applications in early and late summer, peak flux rates were observed as early as 2-3 days after the date of application. While this result differs from observations in other injection studies, it is in keeping with the reasoning behind the delayed peaks. Most nitrogen in manure is immediately available to plants and soil microbes in the form of $NH_4^+$. After a period of time, *Nitrosomonas* and *Nitrobacter* bacteria in the soil have converted most $NH_4^+$ to $NO_3^-$, a form that is available plants, but also prone to leaching and denitrification loss. When manure is injected with the intention of corn production, it is applied only in the spring, because the crop is not harvested until late in the fall. However, in this study, manure was applied several times throughout the growing season. In the later applications, the air and soil temperature were much warmer, so the soil microbes were likely more abundant, active, and are able to convert $NH_4^+$ to $NO_3^-$ more rapidly, resulting in a more rapid peak flux of $N_2O$ from denitrification.

$N_2O$ emissions were sampled 22 times in 2015, 23 times in 2016, and 15 times in 2017. Of those sampling dates, significant differences were noted 10 times in 2015, 14 times in 2016, and 10 times in 2017. At nearly all dates with a significant difference in $N_2O$ flux, the flux was greater in the injected plots than in either the surface-applied or control plots. On dates with elevated emissions, the rate of emission was 3- to 5-fold higher in injected plots compared to surface-applied plots. Differences were significant most consistently on dates with greater emissions, and especially dates with peak emissions. On other days with lower emission rates, treatments were very similar. This phenomenon was especially evident on dates with peak $N_2O$ flux that occurred soon after manure application.

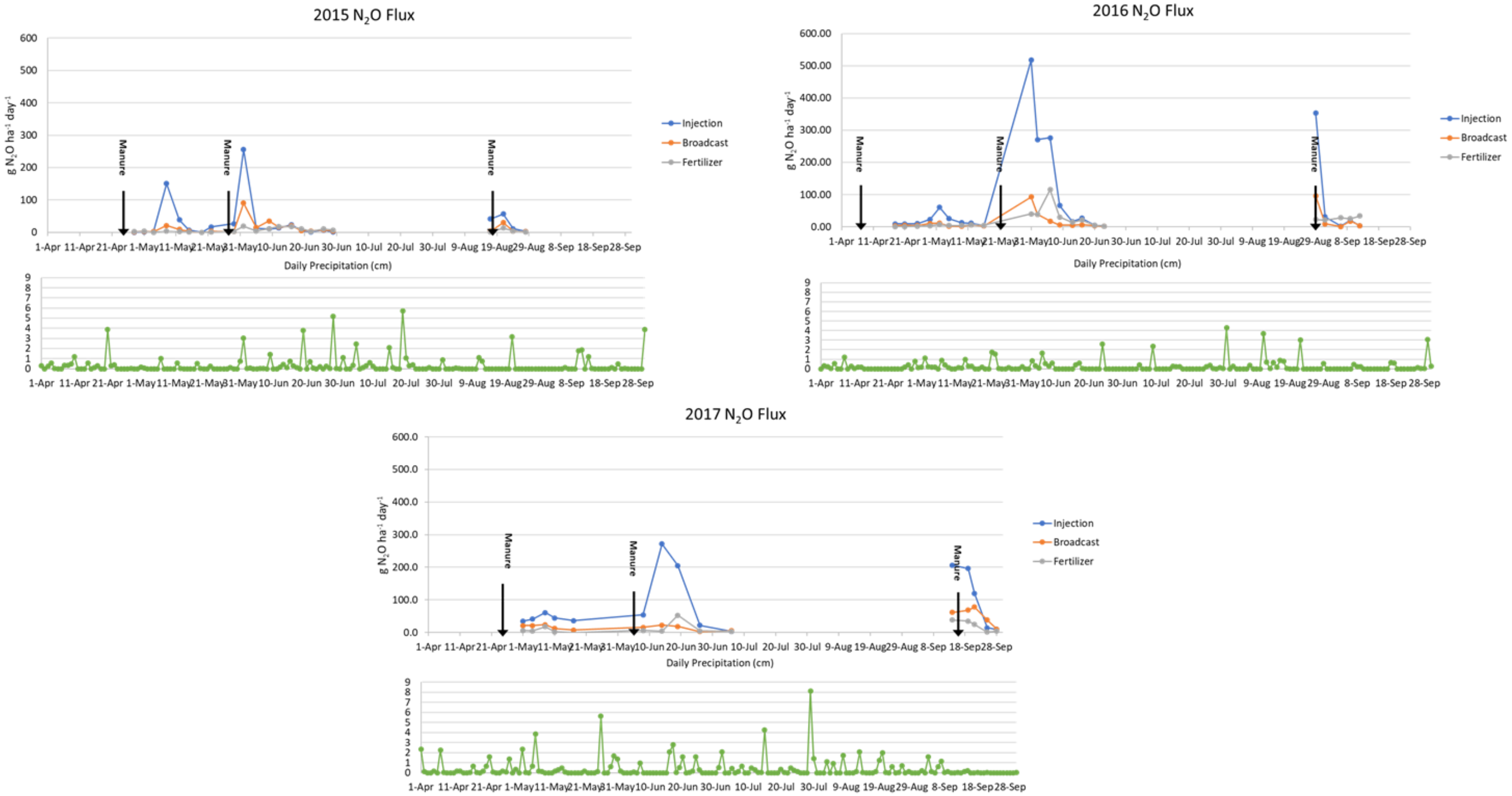


**Figure 3. Measured $N_2O$ emission flux by treatment**

In this study, a peak in $N_2O$ flux was observed near to the manure application date when the greatest amount of nitrate is likely in the soil and available for loss to denitrification. The amount of $N_2O$ lost to denitrification has been found in other studies to be extremely dependent upon soil moisture (Sadeghpour et al, 2018; Louro et al, 2016). In this study, the amount of moisture in the soil was somewhat important in impacting the amount of $N_2O$ emitted at manure application. Figure 3 illustrates the relationship between precipitation and $N_2O$ flux rate. There was a greater amount of precipitation received between the first and second manure applications in 2016 than 2015. As a result, the soil contained more moisture, and the peak $N_2O$ flux was approximately 1.7 times greater in 2016.

Cumulative $N_2O$ emissions were also greater in injected plots than in either broadcast or control measurements at most treatment dates. Cumulative $N_2O$ emissions are compared in Table 3 on a harvest basis. Because no manure was applied between the second and third harvest, values from the third harvest of each season are not included in Table 3.

It is important to note the flaws and potential for error in this calculation of cumulative $N_2O$ release throughout the season. In this calculation, $N_2O$ emission rate was assumed to increase or decrease in a linear manner between measurement dates. While this assumption is considered generally accurate, it allows for the possibility of missed peaks between measurements. In addition, the assumption of a linear rate of change in flux rate may not fully represent a rapid drop in emission rates. As a result, the calculated values presented in this paper may either under- or over-estimate the actual cumulative $N_2O$ release over the course of the growing season.

**Table 3. Comparison of cumulative $N_2O$ emissions and harvested yield**

| Harvest Date | | Yield (kg DM $ha^{-1}$) | Cumulative $N_2O$ (g $ha^{-1}$) | g $N_2O$ kg $DM^{-1}$ |
|---|---|---|---|---|
| 24-May 2015 | INJ | $1418.6_b$ | $799.6_a$ | $0.56_a$ |
| | BRD | $1728.7_{a,b}$ | $147.9_b$ | $0.09_b$ |
| | FERT | $2046.8_a$ | $43.8_b$ | $0.02_b$ |
| 29-Jun 2015 | INJ | $2334.0_a$ | $1202.3_a$ | $0.50_a$ |
| | BRD | $1456.6_c$ | $695.4_{a,b}$ | $0.48_a$ |
| | FERT | $1875.0_b$ | $346.0_b$ | $0.18_b$ |
| 5-Oct 2015 | INJ | $2036.2_a$ | $334.8_a$ | $0.17_a$ |
| | BRD | $1633.9_a$ | $133.7_b$ | $0.09_{a,b}$ |
| | FERT | $1762.9_a$ | $67.1_b$ | $0.04_b$ |
| 23-May 2016 | INJ | $4553.9_a$ | $538.5_a$ | $0.13_a$ |
| | BRD | $4082.1_a$ | $146.7_b$ | $0.04_b$ |
| | FERT | $2937.0_a$ | $104.8_b$ | $0.04_b$ |
| 28-Jun 2016 | INJ | $2356.4_b$ | $2558.5_a$ | $1.13_a$ |
| | BRD | $1971.8_b$ | $324.8_b$ | $0.16_b$ |
| | FERT | $3786.2_a$ | $806.0_b$ | $0.21_b$ |
| 17-Oct 2016 | INJ | $1447.3_a$ | $539.1_a$ | $0.35_a$ |
| | BRD | $1013.8_b$ | $189.6_a$ | $0.19_a$ |
| | FERT | $847.7_b$ | $334.5_a$ | $0.49_a$ |
| 30-May 2017 | INJ | $5798.9_a$ | $715.4_a$ | $0.13_a$ |
| | BRD | $5882.4_a$ | $262.6_b$ | $0.04_b$ |
| | FERT | $4258.3_b$ | $139.8_b$ | $0.03_b$ |
| 18-Jul 2017 | INJ | $2746.3_b$ | $2034.4_a$ | $0.61_a$ |
| | BRD | $2592.5_b$ | $278.3_b$ | $0.11_b$ |
| | FERT | $3832.9_a$ | $359.1_b$ | $0.10_b$ |
| 20-Nov 2017 | INJ | $1913.1_{a,b}$ | $1606.0_a$ | $0.78_a$ |
| | BRD | $1534.5_b$ | $779.9_{a,b}$ | $0.43_{a,b}$ |
| | FERT | $2165.9_a$ | $301.8_b$ | $0.14_b$ |

$*_{a,b,c}$ subscript denotes significant difference between observations at harvest date

The results presented in Table 3 indicate that a greater amount of $N_2O$ was contributed to the atmosphere for each kg of DM yield from the injected plots than either the surface-applied or control plots for a majority of the study. In several cases, the cumulative $N_2O$ was as high as 2-3 times greater in the injection plots than the surface-applied. However, at one harvest date (17-Oct, 2016) there was no significant difference in $N_2O$ emission values per yield. On three other harvest dates (29-Jun, 2015; 5-Oct, 2015; and 20-Nov, 2017), there was no significant difference between surface-applied and injected manure treatments. While some of these examples of similar N2O emission/yield ratios can be explained by an increase in crop yield, the majority of the dates exhibiting similar $N_2O$ emission/yield ratios also experienced similar $N_2O$ emissions.

The largest emission flux was generally observed following the second manure application each year. At this application, the soil was typically still moist from some spring rain, but the soil and air temperature were also warmer at this point in the season than the other two application dates. As a result, the increased amount of soil biological activity at this time may have caused an increase in the rate of release of $N_2O$.

**Nutrient Runoff**

No significant difference was observed between manure application treatments in nutrient runoff collection. Runoff was compared both on an annual (water year) basis, and on individual dates on which large runoff volumes, high runoff concentrations, or both, contributed to a large nutrient load. Table 4 presents the total amount of runoff volume, g $NO_3^-$- N, total nitrogen, particulate phosphorus, dissolved phosphorus, and total phosphorus collected annually for each treatment.

**Table 4. Annual nutrient load from collected surface runoff**

| **Year** | **Treatment** | **Volume** L ha$^{-1}$ | **$NO_3^-$- N** mg ha$^{-1}$ | **Total N** mg ha$^{-1}$ | **Dissolved P** mg ha$^{-1}$ | **Particulate P** mg ha$^{-1}$ | **Total P** mg ha$^{-1}$ |
|---|---|---|---|---|---|---|---|
| 2015 | INJ | $859.7_a$ | $250.6_b$ | $3153.6_a$ | $1068.9_a$ | $538.4_a$ | $1606.9_a$ |
| | BRD | $1251.7_a$ | $328.1_b$ | $3629.2_a$ | $774.9_a$ | $1251.9_a$ | $2026.9_a$ |
| | FERT | $1859.8_a$ | $2118.3_a$ | $8792.4_a$ | $997.1_a$ | $1262.6_a$ | $2259.7_a$ |
| 2016 | INJ | $38.7_{a,b}$ | $202.7_{a,b}$ | $388.8_{a,b}$ | -$^+$ | -$^+$ | $10.2_a$ |
| | BRD | $33.1_b$ | $72.0_b$ | $148.2_b$ | -$^+$ | -$^+$ | $10.2_a$ |
| | FERT | $163.9_a$ | $276.5_a$ | $772.3_a$ | -$^+$ | -$^+$ | $38.3_a$ |
| 2017 | INJ | $91.5_b$ | $201.1_a$ | -$^§$ | $34.1_b$ | -$^§$ | -$^§$ |
| | BRD | $317.2_{a,b}$ | $185.2_a$ | -$^§$ | $110.5_b$ | -$^§$ | -$^§$ |
| | FERT | $471.7_a$ | $782.3_a$ | -$^§$ | $405.1_a$ | -$^§$ | -$^§$ |

$_{a,b}$ subscript denotes significant difference between treatments for a given measurement
$^+$dissolved P and particulate P measurements not available for 2016
$^§$total N, particulate P, and total P measurements not available for 2017

As indicated in Table 4, there were no significant differences between the two manured treatments in any of the measured nutrient categories. In some cases, there was a significant difference between the manured plots and control plots. The total runoff volume was greater in the control than at least one of the manure treatments in 2 out of 3 years. This observation, along with the greater solubility of the fertilizer material likely led to the greater nutrient loads observed in nitrate-nitrogen in 2015 and 2016, as well as the greater amount of total N in 2016 N dissolved phosphorus in 2017 from the inorganic fertilizer compared to the injected manure treatment.

These values for nutrient runoff load are much lower than those observed in similar manure application studies in corn at this site (Johnson et al., 2011). The soils at this site are well drained and only gently sloping. This factor, coupled with the perennial cover of the grass, help to explain the small amount of runoff that was collected throughout the duration of the study. In addition, a lack of precipitation throughout the summer in 2016 resulted in an extremely low volume of runoff water.

The observations indicate a large variation between measured values for each plot. This particular research site is flat, and not conducive to regular runoff. As a result, the observations are variable, so a large difference can still be considered insignificant at the p=0.05 confidence level.

There were very few dates in which a large flow of runoff water was observed. The perennial crop prevented a large amount of infiltration excess, or precipitation that occurs at a greater rate than the soil is able to absorb it, from reaching the collection area. On three individual dates (21-Jul, 2015; 14-Sep, 2015; 1-Aug, 2017), the runoff volume from the plots was large due to a large precipitation event. The concentration of nutrients contained in runoff from each treatment at these events are illustrated in Figures 4-7. No significant difference was observed between injection and surface-applied plots at any of the selected dates. Significant differences between control averages and averages in manured plots are denoted with the asterisk symbol.

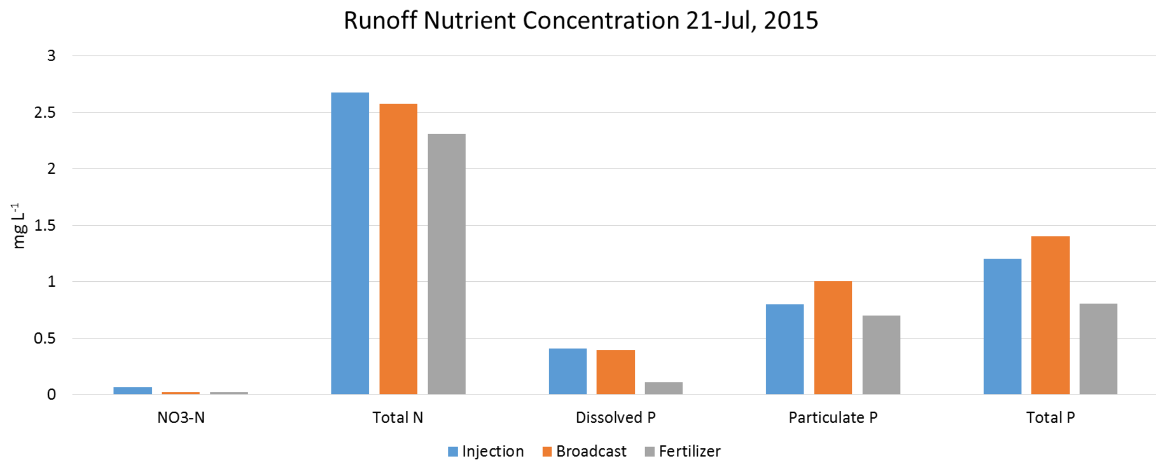


**Figure 4. Concentrations of nutrients in runoff collected on 21-Jul, 2015**

The storm associated with the runoff collected on 21-Jul, 2015 (Fig. 4) occurred 51 days after manure application. As a result, the amount of nutrients that were available for loss on the surface of the soil was quite low. At this interval after manure application, the majority of the nutrients had likely either been lost as gas to the atmosphere, taken up by the plants, or sorbed to soil particles and were likely not available for loss in runoff water. The concentration of nutrients in the runoff were very low compared to the runoff event that occurred in September 2015 (Figure 5).

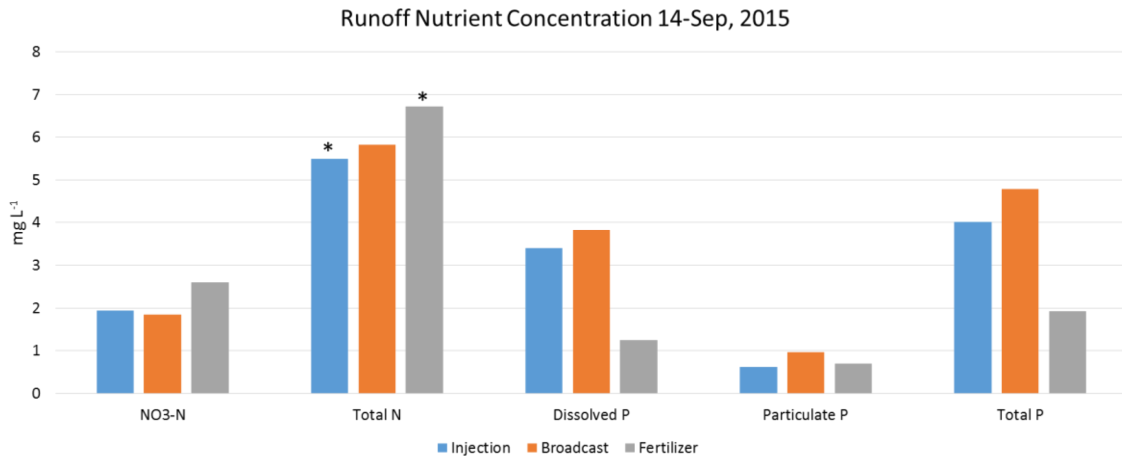


**Figure 5. Concentrations of nutrients in runoff collected on 14-Sep, 2015**

Nutrient concentrations contained in the runoff water collected on 14-Sep, 2015 (Figure 5) were much higher than in the runoff water collected on 21-Jul, 2015. This was likely because of a large precipitation event close in time to the application of manure, that resulted in an infiltration excess and a large amount of runoff took place only 6 days after manure application. As a result, a much larger proportion of the applied nutrients were available on or near the surfaces of the soil and were vulnerable to loss with surface runoff water. The timing of the fertility application also explains the 18% reduction in total nitrogen loss from the control treatment to the injected treatment. When manure is applied, approximately half of the nitrogen remains a component of the organic matter structure in proteins, lignin, and other molecules. As a result, this organic matter was more protected at its deeper location in the soil. Additionally, all of the nitrogen applied to the control plots was applied as urea in 2015 and was therefore highly soluble. Nitrogen from the control plots was also collected in considerable amounts in the ammonium form (not included in Figure 5).

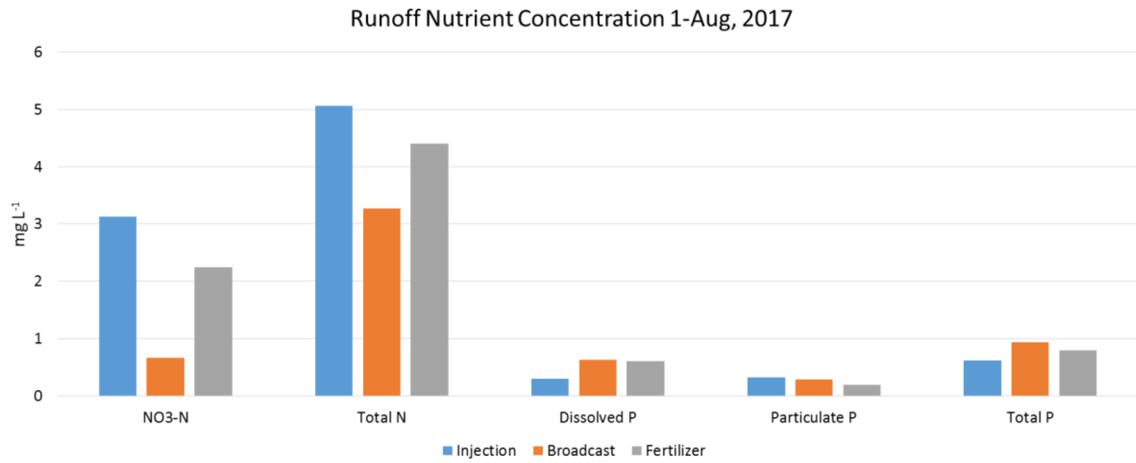


**Figure 6. Concentrations of nutrients in runoff collected on 1-Aug, 2017**

On 1-Aug, 2017, the precipitation event that caused the runoff occurred 52 days after the application of manure and fertilizer (Figure 6). During this event, the volume of runoff was close to the volume collected from the 14-Sep, 2015 event (Figure 7). However, the concentrations of nutrients, especially phosphorus, were lower than on the 14-Sept, 2015 event. Again, this reduction is partially explained by the length of time between the application of manure and the precipitation event that caused runoff from the plots. Over the 52 days between the event and the manure application, the nutrients were secured in the system in some manner and were less available to surface runoff loss. The grass was taller on 1-Aug, 2017 than on 14-Sept, 2015 due to the length of time since the last harvest. As a result, the grass had a greater amount of time to take up the nutrients that had been applied, leaving less available for loss to surface runoff. The grass also may have interfered with the flow of runoff water and the nutrients contained in that water, preventing their flow to the collection units. Finally, the nutrients had more of an opportunity to infiltrate into the soil and either become sorbed to soil particles or to be lost to leaching, a factor that was not measured as a part of this study.

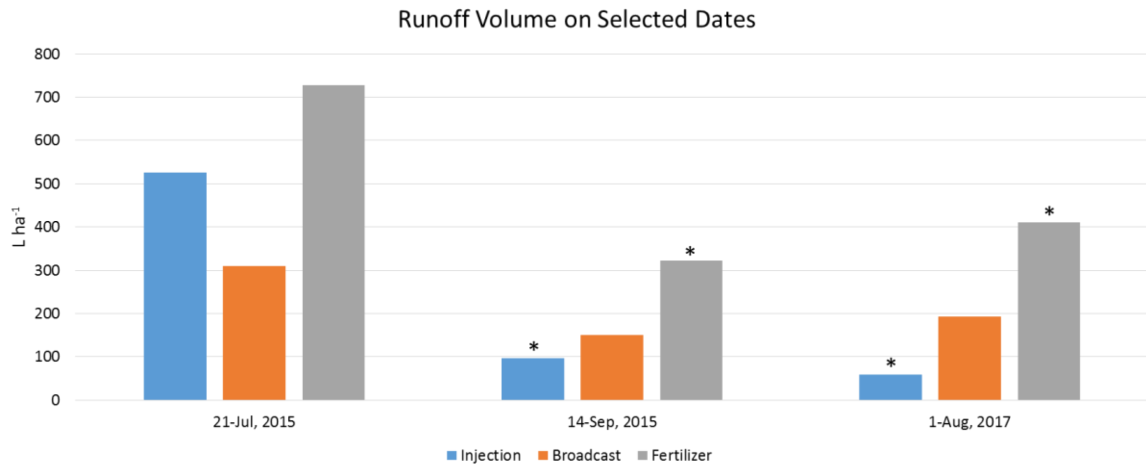


**Figure 7. Volume of runoff associated with sample collection date (Volume of runoff from storm)**

Overall, these results do not indicate that the injection of manure has any benefit in preventing nutrient loss to surface runoff over broadcasting the material. Instead, loss of nutrients to surface runoff is best avoided through the timing of the manure application. If the manure is applied well in advance of a strong precipitation event, the amount of nutrients lost to surface water flow is reduced. However, when nutrients are applied in close proximity to a large precipitation event, there may be some benefit in nutrient conservation in injecting a material with a lower solubility of nutrients, as opposed to applying a soluble chemical fertilizer on the surface.

# Chapter 4

## Conclusion

Across all three treatments, nutrient losses were lower than the levels anticipated based on similar research in corn systems. This is likely due to the ability of perennial cover to retain nutrients more efficiently. It is especially evident in the similarities between all three treatments in runoff concentrations and total nutrient loads collected in runoff water. Nitrogen and phosphorus were lost from the plots at relatively low concentrations, indicating that the perennial grass cover on the surface of the soil helped to mitigate some of that loss. Manure injection with an open-slot injector still provided an advantage in nitrogen conservation by preventing approximately 50% of the ammonia volatilization. However, the 3-5 fold increase in cumulative $N_2O$ emissions raises some concern because of its role as a greenhouse gas. Without a consistent increase in yield in the injection treatment compared to the surface-application treatment, the additional atmospheric $N_2O$ contribution is difficult to justify. However, the amount of nitrogen lost as $NH_3$ was 3.6 times greater than the amount of nitrogen lost as $N_2O$. Conservation of nitrogen as $NH_3$ can prevent some off-site pollution and later $N_2O$ emissions. Additionally, the production of commercial nitrogen fertilizer is energy intensive, emitting a large amount of $CO_2$. Conservation of nitrogen with injection can help to mitigate the emissions from this source by reducing the amount of commercial fertilizer required to reach a targeted yield.

Further research will be required to determine if and when manure injection is beneficial in perennial grass systems. Investigation in reduced-rate application, like a phosphorus-based manure application rate that is required on some Pennsylvania soils, would be more helpful in determining the value of conserved nitrogen. Many farmers in Pennsylvania choose not to supplement their hayfields with nitrogen in addition to the manure that they apply. With a similar yield response at a lower rate of application, some of the environmental pressure may be reduced per kilogram of yield at a lower manure application rate

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**ACADEMIC VITA**

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## EDUCATION

*The Pennsylvania State University, University Park, PA* Graduation: Spring 2018

Schreyer Honors College | College of Agricultural Sciences

Major: Plant Sciences, Agroecology Option

Minor: Agronomy

## INTERNSHIP EXPERIENCE

*Bayer CropScience, Sales Excellence Intern, Colonial Sales District*……………....May 2017-August 2017

- Maintained and collected samples for new product research
- Provided basic technical support for over $1 million in product
- Represented Bayer at a variety of summer commodity meetings

## WORK EXPERIENCE

*USDA Agricultural Research Service, Field Assistant, University Park, PA*……………May 2016-Present

- Process soil samples including grinding and rock separation for further analysis
- Collect gas samples for nitrous oxide concentration analysis according to a specific project plan
- Harvest and label experimental pasture and forage grass samples

*Baxter Farm, Family Farmer, Columbia Cross Roads, PA*…………………………...June 2008-March 2017

- Selected optimal mates and bred mature dairy cattle
- Performed routine chores to ensure maximum production efficiency and sanitation
- Managed alfalfa hay and corn silage fields throughout the growing season

## RESEARCH EXPERIENCE

*USDA Agricultural Research Service, University Park*……………………………….April 2017- Present

- Collected and analyzed gas, soil, and biomass samples following a specified research design plan
- Summarized data into report for submission to Schreyer Honors College

## ACTIVITIES

*Ag Advocates*………………………………………………………………….......August 2016- Present

Selected to represent the College of Agricultural Sciences to prospective students as well as industry representatives

*Coaly Honors Society*…………………………………………………....................December 2016- Present

Selected by current members based on leadership experiences in clubs and organizations

- President- 2017-2018

*Collegiate FFA*…………………………………………………………………....August 2015- Present

Organization comprised of individuals passionate about Ag Literacy and Community Service

- President- 2017

*Dairy Science Club*……………………………………………………....................August 2015- Present

Offers members opportunities to interact with professionals in all aspects of the dairy industry

- Holiday Cheese Box Sale Co-Chair- 2017
  - Coordinated sale and delivery of over 2,500 boxes of perishable product to 48 states
  - Managed 20 volunteers for a period of two weeks to ensure accurate packaging and shipping

*Agricultural Student Council*…………………………………………………August 2016-December 2017

Composite organization of Ag Sciences Clubs that encourages collaboration between members

- 2017- Vice President

*Competitive Teams*……………………………………………………..………January 2017- January 2018

- Forage Bowl Team | 2017, 2018 National Champions
- Weed Science Team | 2017 4th Place Individual, 5th Place team