Nitrous Oxide Emissions from Surface versus Injected Manure in Perennial Hay Crops

Injecting manure can preserve N, but may mechanically damage the root systems of hay crops such as tall fescue (Festuca arundinacea L.) and alfalfa (Medicago sativa L.). Such damage could result in reduced yield. The objective of this study was to compare the effect of disk-injected versus surface applied liquid dairy manure on (i) alfalfa and tall fescue dry matter (DM) yield and (ii) nitrous oxide (N₂O) emissions. Two manure application methods (injection versus surface application) and two no-manure controls (injection versus no soil disturbance) were replicated six times in 2014 and 2015 on established hay stands. Manure application increased alfalfa yield from 2.9 to 3.7 and from 4.2 to 5.1 Mg DM ha⁻¹ in 2014 and 2015, respectively, regardless of application method, suggesting no yield penalty or benefit from injection. Nitrous oxide emissions increased two- and six-fold with manure addition, consistent with higher yields under manure application. Compared with the control treatments, manure addition to tall fescue increased yield by 0.8 and 3.3 Mg ha⁻¹ in 2014 and 2015, respectively, also with no yield benefit or penalty from injection. Injection of manure did not influence N₂O emissions in 2014, but increased emissions by 35% compared with surface application in 2015, and this is consistent with differences in soil moisture that year. Our results indicate injection of liquid manure can be implemented without negatively influencing yield in hay crops, while the impact on N₂O emissions can be crop and weather dependent. When injection does not increase yield, the surface application of manure to hay crops is more economical.

Abbreviations: DM, dry matter; VWC, soil volumetric water content.

Manure management is of critical importance for the sustainability of the dairy industry. The way manure is managed on farm fields affects not only recycling of nutrients and whole farm nutrient balances, but also the emission of greenhouse gases. The methods in which manure is applied can greatly influence both crop yield and the risk of nutrient loss to the environment (Meisinger et al., 2008; Sadeghpour et al., 2016a, 2016b).

Surface application is a convenient and common method of manure addition to corn (Zea mays L.) and hay crops in New York. While surface application of manure is rapid and relatively inexpensive, it can cause odor issues and increase the risk of ammonia volatilization, nutrient runoff, and leaching (Bitman et al., 1999; Maguire et al., 2011; Sistani et al., 2011; Sadeghpour et al., 2015, 2017a). The tillage-based incorporation of manure can reduce ammonia volatilization and odor issues, but this could also enhance mineralization of soil organic C, be fuel-intensive, and be incompatible with no-till or hay production (Maguire et al., 2011).

Technological advances have provided opportunities to place manure beneath the soil surface through injection, and this method can reduce ammonia volatilization, tillage-induced mineralization of organic matter, and nutrient runoff, and
leaching (Webb et al., 2010; Maguire et al., 2011; Powell et al., 2011). Shallow-disk injection has gained popularity as a way to apply manure to corn fields and, more recently, in forages and no-till row cropping systems in the northeastern United States (Dell et al., 2012). However, farmers are hesitant to use manure injectors for hay fields where injection could damage plant crowns and root systems.

Reports by Rodhe and Etana (2005) and Rodhe and Halling (2014) suggest that injection equipment can reduce yield compared with zero soil disturbance in hay crops. Rodhe and Halling (2014) reported 4%, 6%, and 8% lower yields when hay crops were mechanically disturbed with double disk tines, vertical knives, and vertical and horizontal knife units, respectively. Mattila et al. (2003) reported no differences in meadow fescue (Festuca pratensis L.) and timothy (Phleum pretense L.) yields with manure injection (solid-tine injector, equipped with disk coulter and press wheels), suggesting damage to the sward offset the benefits of manure into grass stands. However, there were no check plots (i.e., no-manure treatment) in Mattila et al. (2003) while in the study by Rodhe and Halling (2014) no manure was applied. Additional research is needed to assess whether mechanical damage through injection might offset the benefit of manure addition to crops that can benefit from the manure. In particular, there is a need for direct comparisons of the effect on yield of manure application method (surface versus injection) that includes mechanical disturbance (disk down no manure) and no-manure as control treatments.

Another concern about injecting manure is a potential for increasing N₂O emissions through conserving the inorganic-N fraction of manure in more concentrated, potentially anaerobic, bands in the soil. Nitrous oxide is a greenhouse gas which on a global warming potential basis is approximately 300-fold more potent than carbon dioxide (CO₂). Nitrous oxide emission is estimated to represent 44% of the annual emissions of greenhouse gases from US agriculture (USEPA, 2014). Soil and fertilizer management practices are primary drivers of N₂O emissions (USEPA, 2014) and soil N₂O emissions mostly occur during denitrification (Meisinger et al., 2008).

In general, it is hypothesized that injection of manure results in favorable conditions for denitrification through saturating the soil, providing greater available NO₃ and labile C (Butterbach-Bahl et al., 2013) which could explain an increase in N₂O emissions (Rubaek et al., 1996; Wulf et al., 2002; Rodhe et al., 2006; Duncan et al., 2017). However, a study by Vallejo et al. (2005) found no differences between manure (pig slurry) injection with a shallow injector system (1.05 N₂O ha⁻¹ yr⁻¹) and surface application (0.73 N₂O ha⁻¹ yr⁻¹) to tall fescue. These inconsistent reports possibly stem from differences in manure types, injection units, soil texture, soil drainage, rate and time of application, and plant species. For example, Wulf et al. (2002) reported threefold greater N₂O emissions with injection (10-cm depth V-shaped slots) versus surface applied slurry manure (70% dairy cow slurry and 30% organic household waste) into grassland. Rodhe et al. (2006) reported fourfold greater N₂O emissions from manure injection (closed-slot shallow injector with disk coulter, tabulator tine and press wheel) compared with surface banding of manure into a grass mixture of red fescue (Festuca rubra L. ‘Rubin’), smooth-stalked meadow (Poa pratensis L. ‘Sobra’) and perennial ryegrass (Lolium perenne L. ‘Pavo’).

To our knowledge there are no studies that document and compare both yield and N₂O emissions from surface-applied versus injected manure to tall fescue and alfalfa hay crops that include no-manure control treatments to evaluate the effect of injection (mechanical process) itself as well. Our objectives were to compare the influence of injection versus surface application of liquid dairy manure on (i) yield and (ii) N₂O emissions for established perennial grass (tall fescue) and legume (alfalfa).

**MATERIALS AND METHODS**

**Experimental Site**

In 2014, two field experiments (alfalfa and tall fescue) were conducted in Aurora, NY (42.73°N, 76.65°W, 253 m a.s.l.). The experimental area for the alfalfa study had been in corn from 2005 through 2010, and was seeded to alfalfa in 2011. Thus, the stand was in its fourth year at the onset of the manure injection studies, typically the time when alfalfa stands are rotated to corn on dairy farms. Tall fescue was also planted in 2011 and mowed only once a year. This field had no manure history prior to the manure applications in 2014. The soil type for the alfalfa trials was mostly a mixture of Kendaa (fine-loamy, mixed, semiactive, nonacid, mesic Aeric Endoaquepts) and Lyons (fine-loamy, mixed, active, nonacid, mesic Mollic Endoaquepts). In the tall fescue trial, the soil type was a mixture of Lima silt loam (fine-loamy, mixed, active, mesic Oxyaquic Hapludalfs), Kendaa, and Lyons. In the alfalfa study, the initial soil pH (0–20 cm depth) was 7.5, soil organic matter content was 26 g kg⁻¹, and Morgan-extractable NO₃–N, soil test P, and soil test K concentrations were 8.7, 5, and 59 mg kg⁻¹, respectively. Morgan-extractable soil test Mg, Zn, and Mn concentrations were 320, 0.5, and 21.5 mg kg⁻¹, respectively, while hot water extractable B was 0.5 mg kg⁻¹. In the tall fescue study, the initial pH was 7.2, soil organic matter was 33 g kg⁻¹, and Morgan-extractable NO₃–N, soil test P, and soil test K concentrations were 5.9, 6, and 73 mg kg⁻¹, respectively. Morgan-extractable Mg, Zn, and Mn concentrations were 345, 1.6, and 23.0 mg kg⁻¹, respectively, while hot water extractable B was 0.7 mg kg⁻¹. At both sites, the soil was classified as high in P, K, and Mg, medium (alfalfa site) or high (tall fescue site) in Zn, medium in B and sufficient in Mn according to New York guidelines for hay crops (Ketterings et al., 2003a, 2003b; Cornell Cooperative Extension, 2016).

In 2014, mean air temperatures in June, July, August, September, and October were 20, 20, 19, 16, and 12°C, respectively. The mean air temperature in 2015 was 18°C in June, 21°C in July, 20°C in August, 19°C in September, and 10°C in October. In 2014, cumulative monthly precipitation amounted to 70, 110, 108, 56, and 54 mm for June through October. Cumulative monthly precipitation in 2015 was 210 mm in June,
Manure Sampling and Analysis

Liquid dairy manure (separated liquids) was provided by a neighboring dairy farm. Using a plug-flow biogas recirculation unit, solids were separated from liquids through influent heating, plug-flow digestion, biogas recirculation and utilization, followed by separation of post-digested effluent (Gooch and Pronto, 2009). Prior to land-application of the separated liquids three subsamples were collected and frozen until laboratory analysis could be performed. Briefly, total N was determined via combustion by an Elementar Vario Max (Elementar Analysensysteme, Hanau, Germany). Ammonium N and NO$_3$-N were determined with a Lachat QuickChem 8000 flow injection calorimetric analyzer (Lachat Instruments, Loveland, CO). To determine P and K, nitric acid digestion in a CEM Mars Express microwave (CEM Corporation, Matthews, NC) was used and digested samples were analyzed in a Thermo Scientific iCAP 6500 inductively coupled plasma–atomic emission spectrometer (Thermo Electron Corp., Waltham, MA). Total solids were determined gravimetrically (oven at 100°C for 16 h) (Hoskins et al., 2003). Manure composition is reported in Table 1.

Experimental Design and Treatments

The experiments were conducted in 2014 and 2015 and used a randomized complete block design with two manure treatments, two control treatments, and six replicates. The two manure treatments were: (1) injection of liquid dairy manure and (2) surface application of liquid dairy manure. The control treatments were: (1) “disk down no manure” (injector disks slicing the soil to a depth of approximately 6 to 8 cm without manure being applied) and (2) no manure addition or slicing of soil (Fig. 1). No additional inorganic fertilizer was applied to either alfalfa or tall fescue during the study. Application rates for the manure treatments were: (1) injection of liquid dairy manure; (2) surface treatments, manure was applied in bands with the coulters (disks) above the soil. Manure was applied once a year in the alfalfa trial (directly after first cutting) versus twice a year (following first and third cuttings) for tall fescue. Applications after the first cutting took place on 17 June in 2014 and 2015 for both trials. Fall application of manure (tall fescue trial only) occurred on 2 September and 25 August in 2014 and 2015, respectively. Application rates were different from year to year due to equipment availability.

### Table 1. Application rates and characteristics of liquid dairy manure applied to alfalfa and tall fescue from 2014 to 2015 (nutrient measurements are on a dry weight basis).

<table>
<thead>
<tr>
<th>Year</th>
<th>Spring</th>
<th>Fall</th>
<th>Total N</th>
<th>Ammonium N</th>
<th>Organic N</th>
<th>Total solids</th>
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</tr>
<tr>
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<td>0.8</td>
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</tr>
<tr>
<td>2014</td>
<td>37</td>
<td>0</td>
<td>2.7</td>
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<td>49.3</td>
</tr>
<tr>
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<td>0.7</td>
<td>1.3</td>
<td>36.0</td>
</tr>
<tr>
<td>2015</td>
<td>75</td>
<td>0</td>
<td>2.1</td>
<td>1.3</td>
<td>0.8</td>
<td>26.4</td>
</tr>
<tr>
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<td>2.6</td>
<td>1.1</td>
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<td>52.8</td>
</tr>
</tbody>
</table>

Fig. 1. Four treatments were used in tall fescue: (A) disk down no manure, in which the injector disks sliced the soil to a depth of approximately 6 to 8 cm with no manure applied; (B) injected liquid dairy manure; (C) no manure addition or slicing of soil; and (D) surface-applied manure.
Alfalfa and Tall Fescue Tissue Sampling and Analysis

In 2014, alfalfa was harvested three times (11 July, 21 August, and 12 November). The tall fescue stand was harvested twice (21 August and 12 November) due to low yields that year, reflecting the 2014 drought. In 2015, both crops were harvested four times (12 June, 17 July, 18 August, and 27 October). Harvests were initiated for alfalfa when 10% of plants had started to flower. Tall fescue biomass sampling was based on a typical commercial farms sampling protocol (35-d interval) in New York. At each harvest, 0.6 m² (3 frames of 0.2 m² placed perpendicular to injection bands) were harvested with grass shears (GS model 700; Black and Decker Inc., Towson, MD) at 10 cm above the ground. Once harvested, samples were dried in an oven (60°C) for at least 48 h to determine the dry weight. The oven-dried subsamples were ground to pass a 1-mm screen and analyzed for crude protein as per AOAC (2000) at Cumberland Valley Analytical Services, Inc., Hagerstown, MD. Crude protein data were divided by 6.25 and reported as N concentration in the plant tissues. Nitrogen removal was calculated as kg DM yield ha⁻¹ × %N in the plant tissue.

Soil NO₃–N Sampling and Analysis

Soil samples (10 cores in each plot) were collected (0–20 cm depth) at each harvest time. Each composite soil sample was placed in an ice-filled cooler immediately after collection. Soil samples were oven-dried (<50°C) for at least 48 h on arrival at the laboratory and crushed to pass 2 mm before analysis following standard soil preparation procedures in the Northeast (Griffith et al., 2011). The Morgan extraction was used to extract soil NO₃–N (Morgan, 1941) and a Technicon Autoanalyzer I (Pulse Instrumentation Ltd., Saskatoon, SK, Canada) was used for colorimetric determination of NO₃–N in solution (Murphy and Riley, 1962).

Soil N₂O Emissions

To measure N₂O fluxes, vented chambers were constructed from stainless steel cafeteria serving pans (Vollrath Corporation, Sheboygan, WI) with a port on top for sampling by needle and syringe (Dell et al., 2014). Foam rubber strips were attached to the lower lip of the chamber to form an airtight seal after installing the chambers in the soil. Chamber bases (10-cm height) were created from the bottoms of the additional serving pans. One base was installed (approximately 5 cm in the soil) in every plot prior to measuring N₂O emissions. At each harvesting event, bases were removed and after harvest re-installed for the remaining sampling period. At each sampling time, the chamber top was placed on the base with four large binder clips. Air samples (30 mL) were removed by a syringe and a needle at 0, 15, 30, and 45 min after chamber deployment and transferred into evacuated 12.5-mL exetainers (Labco Ltd., Lampeter, United Kingdom) right after removal from the chamber. In alfalfa, air was sampled 25 times in 2014 and 14 times in 2015. In tall fescue, air was sampled 32 times in 2014 and 21 times in 2015. Air sampling was more intensive (at least three times a week) directly after manure application and before and after rainfall events. After about 2 mo following manure addition air sampling frequency was reduced to once a week or biweekly following the USDA–ARS GraceNet protocol (Parkin and Venterea, 2010).

The analysis of N₂O in the exetainers was performed with an Agilent 7890A (G3440A, Agilent Technologies, Santa Clara, CA) gas chromatogram system (GC) with a flame ionization detector (FID) and an electron capture detector (ECD) (Christen et al., 2014). Samples were injected by a Combi-Pal autosampler (CTC Analytics, Zwingen, Switzerland) capable of sampling 100 exetainers. Samples were drawn from the exetainers by a 2.5-mL N₂ purged glass syringe, with HD-Type PTFE tipped syringe plunger and 23-gauge needle (CTC Analytics AG, Zwingen, Switzerland) and injected into the GC stainless steel, heated (110°C) purged-packed inlet using N₂ (99.999%) as a carrier gas with a flow rate of 21 mL min⁻¹ at constant flow (column 1) and 22.3 mL min⁻¹ (column 2) at constant pressure (Christen et al., 2014).

Nitrous oxide concentration was regressed linearly versus time since closure of the chamber top to calculate N₂O fluxes. At dates with high N₂O emissions, linear regression was always the best fit for the emission data. Occasionally, at dates with low or very low emissions, regression of N₂O emission at the latest sampling time (45 min) against time resulted in a nonlinear response. When this happened, only the initial three measurements were included to obtain linear regressions for all sampling events as suggested by Collier et al. (2014). Summed N₂O emissions were estimated by adding all the N₂O emissions at each sampling date over time (Sadeghpour et al., 2017c). The summed N₂O emission is used for treatment comparisons only. These results should not be interpreted as total seasonal emissions in the absolute sense as our emission measurements were not continuous throughout the seasons but rather discrete sampling times.

A field scout TDR soil moisture meter (Spectrum Technologies, Inc., Aurora, IL) was used to measure soil volumetric water content (VWC) from 0- to 12-cm depth at each sampling date. Along with soil moisture, soil temperature (0–10 cm depth) was monitored at each sampling date with a soil dial thermometer (Reotemp, San Diego, CA).

Statistical Analysis

Data for alfalfa and tall fescue yields, N concentration and N₂O emissions at each sampling date and cumulative soil N₂O emissions were analyzed with PROC Mixed (Littell et al., 1996; SAS Institute, 2009). Data for N₂O emissions were not normally distributed, therefore, they were log₂ transformed before analysis. Due to variability in weather patterns, the potential for carryover of N benefits from liquid manure in 2014 into 2015, and the application of a higher manure rate in 2015 (equipment availability), we analyzed data by year. To evaluate the differences among the four treatments, data for each year were analyzed with treatments as fixed effects, and block as random effect. When there were no interactions between manure rate (with or without) and method (injection versus surface), data for the plots that had received manure (injected or surface applied) were also pooled and analyzed.
against the two no-manure controls (disk down no manure and no manure) to evaluate the effect of manure addition with treatment (manure versus no manure) as the fixed effect and block as a random effect. Similarly, to analyze the effect of injection as method of application versus surface or no application, data for injection (manure injection and disk down no manure) were pooled and analyzed against surface application and no manure addition (pooled) with similar statistical approach. To analyze soil \( \text{NO}_3^- \) and \( \text{N}_2\text{O} \) trends, treatment was considered a main effect for each sampling date and block was considered a random effect. The sum of \( \text{N}_2\text{O} \) emissions (all sampling events combined) was analyzed with treatment as the fixed effect and block as a random effect. Least square means were separated using the PDIFF option of LSMEANS in SAS PROC Mixed; least significant differences (LSD) values are reported at \( P = 0.05 \).

**RESULTS AND DISCUSSION**

**Yield and Nitrogen Removal**

**Alfalfa**

In 2014, alfalfa yields were similar among the two control treatments (no manure and disk down no manure) and ranged from 2.8 to 2.9 Mg DM ha\(^{-1}\) (excluding first cutting). Alfalfa yield increased by 22% with addition of manure regardless of application method that year (Table 2). It should be recognized that lack of yield increase with manure injection versus surface application implies an economic disadvantage for manure injection as surface application of manure is less costly. In 2015, alfalfa yield averaged 4.2 Mg DM ha\(^{-1}\) (including first cutting) when no manure was applied versus 5.1 Mg DM ha\(^{-1}\) where manure had been applied, also independent of method. The yields for the two manure application methods (injection versus surface application) were not significantly different and alfalfa yields in the manured plots were comparable to the statewide averages for alfalfa that year (USDA–NASS, 2015). These combined results suggest that any mechanical damage to roots by the disks of the injector unit used in our study did not reduce yield. These findings are different from those reported by Rodhe and Halling (2014) and could reflect differences in injector units between the studies. In our study, we used a disk injector (rolling coulter blades) which was different from the double disk tine, vertical knife, and vertical and horizontal knife injectors used by Rodhe and Halling (2014). These differences highlight the importance of descriptions of equipment used, in addition to crops, application rates, and manure types.

Manure addition, regardless of application method, increased alfalfa N removal in 2014 and 2015 (Table 2), consistent with yield differences. In 2014, N removal with alfalfa harvest ranged from 89 kg N ha\(^{-1}\) in the two control treatments to 118.3 kg N ha\(^{-1}\) with injection manure. These results suggest that manure injection increased N removal, which is consistent with previous studies (Bloom 2002; Flass et al. 1990).

**Tall Fescue**

In 2014, tall fescue yields were similar among the two control treatments (no manure and disk down no manure) and ranged from 0.5 to 0.7 Mg DM ha\(^{-1}\) (excluding first cutting). Tall fescue yield increased by 70% with addition of manure regardless of application method that year (Table 2). It should be recognized that lack of yield increase with manure injection versus surface application implies an economic disadvantage for manure injection as surface application of manure is less costly. In 2015, tall fescue yield averaged 2.2 Mg DM ha\(^{-1}\) (including first cutting) when no manure was applied versus 3.2 Mg DM ha\(^{-1}\) where manure had been applied, also independent of method. The yields for the two manure application methods (injection versus surface application) were not significantly different and tall fescue yields in the manured plots were comparable to the statewide averages for tall fescue that year (USDA–NASS, 2015). These combined results suggest that any mechanical damage to roots by the disks of the injector unit used in our study did not reduce yield. These findings are different from those reported by Rodhe and Halling (2014) and could reflect differences in injector units between the studies. In our study, we used a disk injector (rolling coulter blades) which was different from the double disk tine, vertical knife, and vertical and horizontal knife injectors used by Rodhe and Halling (2014). These differences highlight the importance of descriptions of equipment used, in addition to crops, application rates, and manure types.

**Table 2.** Dry matter yield, \( N \) removed (\( N_R \)), summed \( \text{N}_2\text{O} \) emissions (\( \Sigma N_2O \)), yield-scaled \( \text{N}_2\text{O} \) emissions (\( \Sigma N_2O/Yield \)), and \( N \) loss through \( \text{N}_2\text{O} \) emissions (\( \Sigma N_2O-N/N_R \)) for alfalfa and tall fescue in 2014 and 2015.

<table>
<thead>
<tr>
<th>Treatment†</th>
<th>Yield ( \text{Mg ha}^{-1} )</th>
<th>( N_R ) ( \text{kg ha}^{-1} )</th>
<th>( \Sigma N_2O ) ( \text{g ha}^{-1} \text{yr}^{-1} )</th>
<th>( \Sigma N_2O/Yield ) ( \text{g N}_2\text{O Mg}^{-1} \text{g N}^{-1} )</th>
<th>( \Sigma N_2O-N/N_R ) ( \text{g N kg N}^{-1} )</th>
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<td>SAM</td>
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† NOM, no manure addition or slicing of soil; DDNM, disk down no manure, in which the injector disks sliced the soil to a depth of approximately 6 to 8 cm with no manure applied; Injection, injected manure; SAM, surface-applied manure.

‡ \( N_R \), dry matter yield multiplied by \( N \) concentration in the tissue of alfalfa and tall fescue to calculate \( N \) removal.

§ Same letters within column by year for alfalfa or tall fescue indicate no significant differences (\( P < 0.05 \)).
to 118 kg N ha\(^{-1}\) where manure had been applied. In 2015, alfalfa N removal was greatest in manured plots (162 kg N ha\(^{-1}\); averaged over injection and surface application), intermediate in the no-manure and no-injection control (135 kg N ha\(^{-1}\)), and least in the disk down no manure treatment (124 kg N ha\(^{-1}\)).

**Tall Fescue**

In 2014, tall fescue yields (0.5 Mg DM ha\(^{-1}\)) were similar between the control treatments (no manure and disk down no manure) and 63% lower than yields obtained in the manure treatments (Table 2). In 2015, yields ranged from 1.8 Mg DM ha\(^{-1}\) (disk down no manure) to 5.4 Mg DM ha\(^{-1}\) (injected manure). Similar to 2014, no differences were found between control treatments in 2015. Manure addition increased the yield of tall fescue regardless of application method, indicating both the benefit of manure addition in the 4- and 5-yr old stands of tall fescue and the lack of a negative effect from running injectors through the stand. Our results are in partial agreement with Mattila et al. (2003) who found no yield differences of meadow fescue and timothy when cattle slurry was injected versus surface applied. Mattila et al. (2003) hypothesized that damage to the sward by the injector offset the benefits of manure into grass stands but their study did not include no-manure control plots to determine whether mechanically damaging the roots was actually reducing the yield.

Injection and surface application of manure increased tall fescue N removal compared with the control treatments in both years. Nitrogen removal was 8 and 34 kg N ha\(^{-1}\) in 2014 (two cuttings) and 2015 (four cuttings), respectively, for plots where no manure had been applied, threefold lower than for plots that had received manure (average of injection and surface application) (Table 2). Tall fescue does not grow well during the drier summer periods in the northeastern United States, and this resulted in low yields and low N uptake. In contrast, the deeper root system of alfalfa typically ensures continued production of alfalfa through dry periods (Jefferson and Cutforth, 2005), one reason why farmers in the northeastern United States prefer seeding of alfalfa over grass where growth conditions are good for alfalfa (well-drained soils).

**Soil NO\(_3\)-N Trend**

**Alfalfa**

The initial soil NO\(_3\)-N concentrations (13 June, 2014) ranged from 8.2 to 9.0 mg kg\(^{-1}\) (Fig. 2). There were no NO\(_3\)-N concentration differences among treatments after the second, third, and fourth cuttings either, with concentrations averaging 5.2, 4.5, and 4.3 mg NO\(_3\)-N kg\(^{-1}\), for each of the three cuttings, respectively. Similar to 2014, there were no treatment differences in soil NO\(_3\)-N concentrations, with levels ranging from 2.8 to 3.2 mg kg\(^{-1}\) on 12 June 2014 prior to manure application, reflecting an extremely wet June (210 mm precipitation) in 2015 (Fig. 2). Soil NO\(_3\)-N remained low throughout the study, with no treatment differences for second cutting (4.7 mg kg\(^{-1}\); averaged over treatments), third cutting (3.4 mg kg\(^{-1}\); averaged over treatments) and fourth cutting (4.0 mg kg\(^{-1}\); averaged over treatments).

**Fig. 2.** Morgan-extractable NO\(_3\)-N of (A) alfalfa in 2014, (B) alfalfa in 2015, (C) tall fescue in 2014, and (D) tall fescue in 2015 as influenced by injected versus surface applied manure: no manure addition or slicing of soil (NOM); disk down no manure (DDNM), in which the injector disks sliced the soil to a depth of approximately 6 to 8 cm with no manure applied; injected manure (injection); and surface-applied manure (SAM).
Tall Fescue

Soil NO$_3$–N in the tall fescue trial was also low with no treatment differences at any of the sampling times. Low soil NO$_3$–N concentrations at the beginning of the growing season are typical of New York due to snowmelt and rainfall events (Sadeghpour et al., 2017b, 2017c). In 2014, averaged over treatments, soil NO$_3$–N levels were 5.9, 4.0, and 2.9 mg kg$^{-1}$ at the first, second, and third cuttings, respectively. In 2015, soil NO$_3$–N levels ranged from 3.1 mg kg$^{-1}$ at first cutting to 3.9 mg kg$^{-1}$ at fourth cutting, similar to what was observed in the alfalfa study. These results show the different nature of perennial hay N uptake versus row crops such as corn and suggest that to capture NO$_3$–N variability shortly after manure application when plant uptake is lower (period of grass regrowth), soil sampling should be done more frequently.

Soil N$_2$O Emissions

Alfalfa

In 2014, baseline (early June) N$_2$O fluxes were small (2.4 g N$_2$O ha$^{-1}$ d$^{-1}$; averaged over all treatments) and similar among all four treatments. Daily N$_2$O fluxes increased approximately 7 d after manure addition in 2014 (Fig. 3, S3). Similar to our finding, Duncan et al. (2017) found it takes 7 d for injected manure (using the same open-slot injector used in this study) to show the first N$_2$O emission peaks. Nitrous oxide fluxes remained low in control plots (disk down no manure and no manure) averaging 5.6 g N$_2$O ha$^{-1}$ d$^{-1}$ over the two control treatments. Nitrous oxide fluxes were 30-fold higher than the baseline (61.3 g N$_2$O ha$^{-1}$ d$^{-1}$) in manure treatments regardless of application method. Thus, a shift from surface application to manure injection did not increase N$_2$O emissions at the first peak in 19 June. On 20 June, a day after the first N$_2$O peak, N$_2$O fluxes remained sevenfold and threefold higher than the baseline sampling in manure (injection and surface application) and no manure control treatments, respectively (Fig. 3). Nitrous oxide levels were as low as the initial levels in the disk down and no manure control treatment (1.8 g N$_2$O ha$^{-1}$ d$^{-1}$). At the major rainfall event (26 June 2014), N$_2$O fluxes were similar between injection and surface application of manure (23.6 g N$_2$O ha$^{-1}$ d$^{-1}$) but twofold higher than treatments without manure addition (disk down no manure and no manure). Nitrous oxide emissions were low (2.7 g N$_2$O ha$^{-1}$ d$^{-1}$; averaged over sampling dates and treatments) and similar among all treatments for the rest of the growing season. Dell et al. (2014) and Duncan et al. (2017) showed very low N$_2$O emissions at the end of the growing season as well, reflecting crop N uptake and low soil NO$_3$–N availability.

In 2015, N$_2$O fluxes were low for the baseline sampling round (0.7 g N$_2$O ha$^{-1}$ d$^{-1}$; averaged over all treatments) and lower than in 2014, reflecting a very wet June (saturated soil conditions) which might have increased N$_2$ emissions rather than N$_2$O emissions, along with threefold lower soil NO$_3$–N levels in 2015. A wet June and higher manure application rate (75 kL ha$^{-1}$) in 2015 resulted in several large emission peaks during June and early July. Daily N$_2$O fluxes increased 5 d sooner than in 2014 (2 d after manure application) where manure treatments (injection and surface application) had 25.5 g N$_2$O ha$^{-1}$ d$^{-1}$, 90% higher than the control treatments (disk down no manure and no manure). This could be due to slightly wetter soil in 2015 than in 2014 at the time of manure application followed by much wetter soil shortly after manure addition in 2015. Dutta
et al. (2015) who showed higher water content coupled with inorganic N availability when microbial activity is high, increased N$_2$O emissions. A shift from surface application to injection did not influence N$_2$O fluxes 7 d after manure application; fluxes for these two treatments averaged 146 g N$_2$O ha$^{-1}$ d$^{-1}$. After 38 mm of rainfall (29 June), N$_2$O fluxes were higher where manure had been injected (13.7 g N$_2$O ha$^{-1}$ d$^{-1}$) than where it had been surface applied (5.3 g N$_2$O ha$^{-1}$ d$^{-1}$) possibly reflecting some ammonia-N conservation where manure had been injected coupled with wet conditions (Duncan et al., 2017). Large N$_2$O fluxes were observed for injected manure (152.6 g N$_2$O ha$^{-1}$ d$^{-1}$) on the second of July and surface applied manure (108.0 g N$_2$O ha$^{-1}$ d$^{-1}$) on 8 July. The earlier emission peak (14 d after manure addition) where manure was injected compared with the peak 20 d after surface application of manure could possibly reflect greater NO$_3$–N availability with injection as well. On 15 July, after 10 mm of rainfall, N$_2$O fluxes were similar between the two manured treatments (injection and surface application) and threefold greater than for both control treatments.

Injecting manure did not increase overall N$_2$O emission (sum of emission of all dates during which emissions were measured) compared with surface application of manure in either year. Summed N$_2$O emissions were 164 and 443 g N$_2$O ha$^{-1}$ yr$^{-1}$ for injected versus 159 and 425 g N$_2$O ha$^{-1}$ yr$^{-1}$ for surface applied manure in 2014 and 2015, respectively (Table 2). A threefold higher N$_2$O flux in 2015 compared with 2014 is also consistent with the higher manure application rate in 2015 combined with a very wet June in 2015. Alfalfa yield increased with manure addition over time consistent with the benefit of manure for revitalizing older hay stands. Our results are different from Duncan et al. (2017) possibly due to differences in site and plant species [alfalfa in our study versus a corn-clover (Trifolium pretense L.) in Duncan et al. (2017)].

**Tall Fescue**

Similar to alfalfa, baseline (early June) N$_2$O fluxes in tall fescue were small (0 g N$_2$O ha$^{-1}$ d$^{-1}$; averaged over all treatments) in 2014. The increase in daily N$_2$O fluxes followed the same trend as for alfalfa and the first emission peak occurred approximately 7 d after manure addition (Fig. 3). Seven days after application, N$_2$O fluxes remained low in the control plots (0.5 g N$_2$O ha$^{-1}$ d$^{-1}$ averaged over disk down no manure and no manure), but averaged 45 g N$_2$O ha$^{-1}$ d$^{-1}$ for the manure treatments, regardless of application method. A shift from surface application to manure injection did not change N$_2$O emissions at the first peak in 19 June (7 d after manure application). Chadwick et al. (2000) suggested a 7 d delay in N$_2$O emissions was a result of the time needed for nitrification to occur. A day after the first N$_2$O peak, N$_2$O fluxes remained high where manure had been injected (32.9 g N$_2$O ha$^{-1}$ d$^{-1}$) and were threefold higher than when manure had been surface applied suggesting possibly higher N availability through N conservation by injection. These results are similar to what is reported in Comfort et al. (1990) and Duncan et al. (2017) who showed early peaks with injecting manure were greater than when manure was surface applied. Comfort et al. (1990) indicated that injecting manure increased denitrification by creating an anaerobic environment with ample readily oxidizable C and available NO$_3$–N.

Emissions after that first peak and prior to fall manure addition were low and similar among all treatments. In contrast, addition of manure in fall (3 September) increased daily N$_2$O fluxes 2 d after manure addition with emissions that were eightfold higher in surface applied manure than where manure had been injected. Three days after application, N$_2$O fluxes remained high but they were no longer statistically different from those measured when manure was injected. The peaks for N$_2$O fluxes occurred 9 d after manure application where manure had been injected, with an N$_2$O flux of 68 g N$_2$O ha$^{-1}$ d$^{-1}$. Nitrous oxide emissions were higher in the fall than in the spring reflecting wetter soil condition in the fall (32% VWC) than in the spring (26% VWC) (Fig. 4), consistent with soil moisture as a primary driver of N$_2$O emissions when NO$_3$–N is available. Soil temperature averaged 23°C in spring, 5°C higher than in the fall period suggesting soil temperature is not a major factor for N$_2$O emissions during the growing season.

In 2015, N$_2$O fluxes were low at the baseline sampling round (0.7 g N$_2$O ha$^{-1}$ d$^{-1}$; averaged over all treatments). Daily N$_2$O fluxes in spring 2015 showed a similar trend to N$_2$O fluxes after manure application in fall 2014, reflecting wet soil conditions. Two days after manure addition, N$_2$O fluxes increased where manure had been surface-applied and were threefold higher than when manure was injected. The highest daily N$_2$O fluxes for surface applied manure were measured 5 d after manure application. The fluxes amounted to 116.9 g N$_2$O ha$^{-1}$ d$^{-1}$, twofold higher than fluxes measured after manure injection (66.0 g N$_2$O ha$^{-1}$ d$^{-1}$). The highest peak for injected manure was 14 d after manure addition (109 g N$_2$O ha$^{-1}$ d$^{-1}$) possibly reflecting a slower release of NO$_3$–N in injected manure when the soil is wet. On the same date, soil N$_2$O fluxes were non-detectable for surface applied manure.

After the initial peaks until fall application of manure N$_2$O emissions were low and not different among treatments consistent with the low NO$_3$–N levels in that period. Daily N$_2$O fluxes increased in the days after fall manure application but remained low throughout the rest of the growing season for both control treatments. Just prior to manure application in the fall, the average of total (summed) emissions in the two manure treatments was 177 g ha$^{-1}$ period$^{-1}$. Daily N$_2$O fluxes increased by twofold with manure injection (26.5 g N$_2$O ha$^{-1}$ d$^{-1}$) and threefold where manure was surface-applied (24.3 g N$_2$O ha$^{-1}$ d$^{-1}$) but differences among treatments were not significant. Nitrous oxide fluxes remained the same 2 d after manure injection but decreased where manure had been surface applied. Injected manure showed another peak 4 d after manure application (46.8 g N$_2$O ha$^{-1}$ d$^{-1}$). This peak did not appear where manure had been surface-applied.

Seven days after manure application, daily N$_2$O fluxes were higher with injection of manure than with surface application.
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This could reflect loss of N through volatilization with surface application and placement of manure in concentrated bands. Volumetric water content was 33% in injected manure versus 26% in surface applied manure in the first 2 d after application which could have further stimulated microbial activity for N\textsubscript{2}O emissions, leading to differences in N\textsubscript{2}O emissions between injection and surface application treatments (Fig. 4).

In 2015, N\textsubscript{2}O fluxes were low for the rest of the growing season (0.9 g N\textsubscript{2}O ha\textsuperscript{-1} d\textsuperscript{-1}; averaged over all treatments) similar to what was observed in 2014. Nitrous oxide fluxes were greater in spring than fall applications (surface and injection) consistent with a VWC of 41% in the spring (averaged over first 8 d after spring manure addition in manured plots) versus 20% in the fall (averaged over first 8 d after fall manure addition in manured plots). Duncan et al. (2017) also reported greater N\textsubscript{2}O emissions in the spring than fall and suggested that fall applying manure could be an option to reduce N\textsubscript{2}O emissions. Further studies are needed with tall fescue and alfalfa to test this hypothesis.

While injecting manure did not increase the sum of N\textsubscript{2}O emissions compared with surface application in 2014, it increased N\textsubscript{2}O emissions in 2015. The sum of N\textsubscript{2}O fluxes ranged from 16.5 g N\textsubscript{2}O ha\textsuperscript{-1} yr\textsuperscript{-1} in the two controls to 238.1 g N\textsubscript{2}O ha\textsuperscript{-1} yr\textsuperscript{-1} where manure was injected. There were no significant differences in summed emissions between the two manure treatments.

In 2015, summed N\textsubscript{2}O emissions ranged from 8.0 g N\textsubscript{2}O ha\textsuperscript{-1} yr\textsuperscript{-1} in the control (disk down no manure) to 348.6 g N\textsubscript{2}O ha\textsuperscript{-1} yr\textsuperscript{-1} where manure was injected. The greater N\textsubscript{2}O emission with manure application in 2015 likely reflected, at least in part, the higher manure application rate in 2015. Injecting manure increased N\textsubscript{2}O fluxes by 35% compared with surface applying manure. Such differences could have stemmed from conservation of ammonia by injecting manure, greater loss of ammonia in surface application of manure due to dry conditions in the fall, and greater initial soil moisture in injected (33% VWC) versus surface applied manure (26% VWC). These results highlight the importance of measuring ammonia emission concurrently with N\textsubscript{2}O fluxes to better determine the effects of injecting manure in perennial grasses and legumes.

**Soil N\textsubscript{2}O Emissions, Yield, and Nitrogen Uptake Alfalfa**

In 2014, there were no differences between yield-scaled N\textsubscript{2}O emission of manured plots (46.1 g N\textsubscript{2}O Mg\textsuperscript{-1}) and controls (26.9 g N\textsubscript{2}O Mg\textsuperscript{-1}; averaged over disk down no manure and no manure). In 2015, there were no differences between plots where manure had been injected (61.7 g N\textsubscript{2}O Mg\textsuperscript{-1}) and surface-applied manure (65.8 g N\textsubscript{2}O Mg\textsuperscript{-1}) while the disk down no manure treatment had significantly lower yield-scaled emissions (10.4 g N\textsubscript{2}O Mg\textsuperscript{-1}). The slightly higher yield-scaled N\textsubscript{2}O emissions for manure plots in 2015 compared with 2014 emphasize that best management practices should include adjustment of rates of application to meet and not exceed crop needs (Van Groeningen et al., 2010).

**Tall Fescue**

No differences were found between yield-scaled N\textsubscript{2}O emissions of surface applied (130.5 g N\textsubscript{2}O Mg\textsuperscript{-1}) versus injected manure (176.0 g N\textsubscript{2}O Mg\textsuperscript{-1}) in 2014 growing season. However, yield-scaled N\textsubscript{2}O emissions were greater in the injected manure (58.2 g N\textsubscript{2}O Mg\textsuperscript{-1}) than surface applied manure (27.9 g N\textsubscript{2}O Mg\textsuperscript{-1}) in 2015. These results combined with a lack...
of difference in yield between the two treatments could suggest that N was not a limiting factor and that N conserved by injection increased excess N and therefore resulted in higher N$_2$O emissions without gaining yield. These findings support the recommendation to adjust application rates to meet crop N needs but reduce N losses. As was the case with alfalfa, N uptake and tall fescue yield were linearly related ($R^2 = 0.99$) and therefore, expressing N$_2$O-N per unit of N uptake did not add new information regarding the dynamics of N$_2$O losses.

**CONCLUSIONS**

Our results suggest that for established alfalfa stands (fourth and fifth year), not limited by N supply, manure application increases N$_2$O emissions regardless of application method. Injection itself (with or without manure addition) did not affect yield or N$_2$O emissions in either of the 2 yr of study, indicating that slicing of the stand with injector disks at 5- to 7.5-cm depth did not have a detrimental effect on alfalfa yield. Injecting manure did not increase N$_2$O emissions compared with surface application of manure in tall fescue in 2014 either but did increase N$_2$O emissions by 35% in 2015, consistent with higher soil moisture content where manure had been injected that year. Our results indicated that manure injection can be implemented without negatively influencing yield in hay crops while impact on N$_2$O emissions can be crop and weather dependent. It should be recognized that injection of manure is more costly to implement than surface application; thus injection can increase the cost of production with the possibility of increasing N$_2$O emissions as well.

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**REFERENCES**


