ABSTRACT

Fall manure applications can lead to nutrient losses prior to spring planting. This 2-yr study evaluated effects of winter cereal rye (Secale cereal L.) crop management (cover crop versus ryelage), and fall, dairy slurry manure application method (broadcasted versus injected) and timing (September vs. November) on manure–N conservation. Nitrogen conservation was calculated from NH₃ volatilization, percentage of manure–N in aboveground rye (%ManureN-R) and soil (%ManureN-S) in spring prior to corn (Zea mays L.) planting, and subsequent corn yield. Ryelage compared to cover crop conserved more %ManureN-R (2.6-fold) and despite reduced corn yield, ryelage treatments with 3.6-fold greater rye biomass produced 20% greater total harvested forage than cover crops. Compared to broadcasted manure (BM), injected manure (IM) reduced NH₃ losses and increased ryelage biomass (42%) after September (EARLY) applications, %ManureN-R (50%), %ManureN-S at multiple depths, and total harvested forage (20%). Corn silage yield with IM compared to BM was also greater after all cover crop treatments (23%), all ryelage treatments in 2015 (35%), and ryelage with a November application (LATE) in 2014 (30%). Compared to EARLY, LATE applications increased %ManureN-R in ryelage after BM (44%) and IM (50%), %ManureN-S at multiple depths in both rye treatments, and corn silage yields with IM following cover crops (21%). Following ryelage, corn yields were not larger following greater %ManureN-S in LATE IM versus BM, suggesting potential for more soil NO₃ leaching loss with LATE IM. However, multiple management options reduced fall manure–N losses and conserved manure–N for crop utilization, allowing for farm management flexibility.

Core Ideas

- Manure application method and timing affected ryelage but not rye cover biomass.
- Manure injection compared to broadcast conserved manure-N in ryelage.
- Manure injection compared to broadcast with rye cover resulted in more corn silage.
- Late injection compared to early injection conserved more manure-N in ryelage.
- Late versus early injection resulted in more manure-N in soil and more corn after cover crops.

In the northeastern United States, it is common for dairy farmers to apply manure throughout the fall due to typical 6-mo manure storage limitations, time constraints, spring soil moisture and compaction concerns (Meisinger and Jokela, 2000), and crop nutrient needs. Although there are practical benefits for farmers, lack of vegetative growth and nutrient uptake make fall and winter manure applications environmentally riskier than applications in spring and summer when crops are actively growing. Fall applications are of particular concern in the Chesapeake Bay, where agricultural sources have been identified as a primary contributor of P and N to the Bay, causing hypoxic conditions that threaten aquatic organisms, human health, and overall water quality (Howarth et al., 2000; Smith, 2003; Verhoeven et al., 2006; Frumin and Gildeeva, 2014). Several states within the Chesapeake Bay have manure management guidelines that restrict applications (Srinivasan et al., 2006; Liu et al., 2018). For instance, Pennsylvania permits fall and winter manure applications, but requires a minimum of 25% ground cover, residue, or established cover crop; or manure must be injected or mechanically incorporated within 5 d using minimal soil disturbance techniques consistent with no-till farming practices (Pennsylvania Code, 2005).

An established cover crop can reduce N leaching losses to the environment compared to bare fields (Tonitto et al., 2006; Martinez-Feria et al., 2016; Hanathana et al., 2018). A meta-analysis of 69 non-legume cover crop studies consisting mostly of winter rye (75% of studies) found that cover crop uptake of inorganic N averaged 37 kg N ha⁻¹ and reduced leaching by 70% compared to bare fallow across a wide range of climate and management systems (Tonitto et al., 2006). In northeastern climates where planting windows are short, winter rye is an ideal species for establishing after corn or soybean (Glycine max L.) (Starzycki, 1976). In addition to being cold tolerant, winter rye is a N


Abbreviations: %ManureN-R, percentage of manure–N in aboveground rye; %ManureN-S, percentage of manure–N in soil; BM, broadcasted manure; CEB, rye cover crop with early-broadcasted manure; CEI, rye cover crop with early-injected manure; CLB, rye cover crop with late-broadcasted manure; CLI, rye cover crop with late-injected manure; CM, crop management; CP, crude protein; EARLY, September manure application; GDD, growing degree days; IM, injected manure; LATE, November manure application; MoMA, method of manure application; RIE, ryelage with early-broadcasted manure; REI, ryelage with late-injected manure; TaA, time after manure application; ToMA, time of manure application.
scavenger and can reduce N leaching (Snapp et al., 2005; Clark, 2007; Komatsuzaki and Wagter, 2015).

Extending winter rye growth and harvesting it for silage extends cover crop soil conservation benefits and removes soil nutrients (Heggenstaller et al., 2008; Krueger et al., 2011; Ketterings et al., 2015a). Compared to no cover crop, rye/age reduced soil nitrate concentrations by 27% in a Minnesota study (Krueger et al., 2012). In Iowa, a triticale-corn grain × (Triticosecale WittMack) double cropped system averaged 74, 41, and 164% increase in N, P, and K removal compared to a sole crop corn biomass production system (Heggenstaller et al., 2008).

Coupling winter rye with N conserving manure application strategies such as manure injection can further reduce N losses from fall manure applications and conserve N for crop production (Singer et al., 2008; Cambardella et al., 2010). Broadcast manure left at the soil surface, a typical practice in no-till systems, can result in substantial losses of plant available N through NH3 volatilization. Loss of NH3–N in manure after surface broadcasted manure without incorporation ranges from 25–90%, with most commonly reported losses ranging from 30–70% (Lauer et al., 1976; Beauchamp et al., 1982; Sommer and Hutchings, 1995; Meisinger and Jokela, 2000; Thompson and Meisinger, 2002; Dell et al., 2011). Others have found that incorporating manure significantly reduced NH3–N losses (Maguire et al., 2011; Dell et al., 2011, 2012; Duncan et al., 2017; Bierer et al., 2017). Shallow disc injection of dairy slurry in spring, reduced NH3–N loss by 90% (Dell et al., 2011) and 92–98% (Duncan et al., 2017) compared to a broadcast application without incorporation. Shallow disc injectors offer additional benefits of maintaining no-till benefits such as retaining surface residues and reducing erosion (Maguire et al., 2011).

Temperature is another factor that drives NH3 volatilization. In Maryland, 19% of NH4 in liquid dairy manure was lost by volatilization after a winter application when air temperatures the week after were cooler (0–10°C), compared to 71% lost after a spring application when temperatures the following week ranged from 5–25°C (Thompson and Meisinger, 2004). Delaying manure spreading until late fall has several advantages including the ability to prioritize earlier winter annual crop planting, favorable soil conditions, and fewer labor constraints compared to spring, and lower temperatures that can reduce NH3 volatilization, N mineralization, and N leaching out of the rootzone (Randall et al., 1999; Thompson and Meisinger, 2002; Srinivasan et al., 2006; van Es et al., 2006).

Although the ability to postpone manure applications could be advantageous, risk of water pollution and increased public concern for water quality has made delayed manure spreading later in fall or winter a contentious or restricted practice (Pennsylvania Code, 2005; Srinivasan et al., 2006; Liu et al., 2018). Several studies have reviewed conflicting research on winter manure spreading and have concluded that nutrient losses from winter applications are complex and not well understood due to environmental and management-related factors (Srinivasan et al., 2006; Liu et al., 2018). Literature on late fall manure applications coupled with cover crops and other manure–N conservation practices is limited. However, some studies have found that manure applications made in late fall, to bare fields following corn harvests when temperatures were below 10°C, reduced the potential for soil nitrate leaching (Randall et al., 1999; Vetsch et al., 2017). Nitrogen availability for a corn crop following a winter cereal crop varies considerably due to cover crop N content, C/N ratio, residue management, soil temperature, and soil type. Various studies suggest that N retained by a rye cover crop can become available in subsequent growing seasons (Doran and Smith, 1991; Thorup-Kristensen and Nielsen, 1998; Garwood et al., 1999; Rosolem et al., 2004; Lacey and Armstrong, 2015; Snapp and Surapur, 2018). In a meta-analysis, the effect of winter cover crops on the following corn yields differed by region (Miguez and Bollero, 2005). Cover cropping in corn systems may be less suitable in Canada and the Northcentral United States (Miguez and Bollero, 2005) than warmer climates, but it has been found to be viable in the mid-Atlantic where the growing season is longer, and particularly if the rye was terminated prior to corn planting and sufficient N was applied (Duiker and Curran, 2005; Miguez and Bollero, 2005; Kettering et al., 2015a; Snapp and Surapur, 2018).

Fall established winter rye has the potential to temporarily sequester N and reduce N leaching and runoff losses to the environment (Tollenaar et al., 1992; Tonitto et al., 2006; Krueger et al., 2011; Cambardella et al., 2010; Kaspar et al., 2012; Komatsuzaki and Wagter, 2015). Further, combining fall-applied dairy with a rye cover crop did not negatively impact the subsequent corn yield compared to no cover crop in Wisconsin (Grabber et al., 2014). Similarly, injecting liquid swine manure after establishing a rye–oat (Avena sativa L.) cover compared to the rye–oat cover without manure in Iowa also did not impact subsequent corn grain yield (Singer et al., 2008). However, in no-till cotton in Mississippi, Tewolde et al. (2015) found that subsurface banding of fall-applied poultry litter to an established winter wheat (Triticum aestivum L.) cover crop increased cotton lint yield relative to no cover crop and integrating the wheat cover crop improved cotton yields over no-cover crop.

The objective of this study was to determine manure application and rye management strategies that would conserve manure–N for crop utilization. We hypothesized that injecting versus broadcasting manure and applying manure in late versus early fall would reduce NH3 volatilization and N mineralization losses and conserve more manure–N for rye/age or subsequent crop utilization. Further, winter rye managed as rye/age would conserve greater manure–N in rye biomass while cover crops would have greater residual soil NO3–N available for a subsequent crop or leaching.

**MATERIALS AND METHODS**

**Site Description**

Research was conducted at the Russell E. Larson Agricultural Research Center in Rock Springs, PA (40°43’ N, 77°56’ W, 372 m elevation). The experiment was initiated in the fall of 2013 and repeated in 2014 on an adjacent field approximately 2.4 km west of the 2013 site. In 2013–2014, the study was conducted on Hagerstown silt loam (fine, mixed, semiactive, mesic Typic Hapludalf) soils with a 3–8% slope. In 2014–2015, soils were Hagerstown silt loam with a 3–8% slope and Nolin silt loam (fine-silty, mixed, active, mesic Dystric Fluventic Urturdepts) with 0–5% slope.

The experiment was a three-way factorial, randomized complete block design with six replications. The three factors evaluated were crop management (CM), winter cereal rye managed as a cover crop or harvested for rye/age; method of manure
Agronomy Journal • Volume 111, Issue 3 • 2019

application (MoMA), manure was either broadcasted (BM) or injected (IM); and time of application (ToMA), manure was applied in September (EARLY) or in November (LATE). The factorial design included a total of eight treatments, each applied in a 4.6 × 9.1 m plot: rye cover crop with manure early-broadcasted (CEB), late-broadcasted (CLB), early-injected (CEI), and late-injected (CLI); and ryelage with manure early-broadcasted (REB), late-broadcasted (RLB), early-injected (REI), and late-injected (RLI).

Agronomic Management

Liquid dairy manure was broadcasted without incorporation, or shallow disk injected EARLY or LATE at a target rate of 42 and 49 Mg ha⁻¹, respectively, in 2013 and 2014. In September, 73 kg NH₄⁺ ha⁻¹ and 122 kg organic N ha⁻¹ and 89 NH₄⁺ ha⁻¹ and 94 organic N ha⁻¹ were applied EARLY in 2013 and 2014, respectively. In November, 58 NH₄⁺ ha⁻¹ and 97 kg organic N ha⁻¹ and 73 kg NH₄⁺ ha⁻¹ and 73 kg organic N ha⁻¹ were applied LATE in 2013 and 2014, respectively. Six broadcast splash-plates and shallow disc injectors (Yetter Mfg, Colchester, IL) were on the same modified tool bar behind the manure spreader. Broadcast splash plates were placed directly behind the shallow disc injectors spaced 75 cm apart to cover an operating width of 4.6 m. Shallow disc injectors sliced the soil and a drop hose placed the manure in the slit approximately 10 to 15 cm below the surface. Closing disks closed the open slit by covering it with soil. EARLY manure was applied on 26 Sept. 2013 and 30 Sept. 2014. LATE manure was applied on 26 Nov. 2013 and 13 Nov. 2014.

Across all treatments, an unnamed variety of winter rye was planted at a seeding rate of 134 kg ha⁻¹ after an EARLY manure application on 5 Oct. 2013 and 13 Oct. 2014, with a Great Plains 1005 solid-stand no-till drill (Great Plains Mfg, Salina, KS) spaced at 19 cm. In 2014, poor rye germination resulted in the replanting of ‘Aroostock’ rye on 20 October at a seeding rate of 134 kg ha⁻¹. When managed as a cover crop, rye was terminated at Feekes growth stage 5 with 0.95 L glyphosate \((\text{N-}(\text{phosphonomethyl})/\text{glycine})\) on 9 May 2014 and 11 May 2015. Cover crop biomass was determined just prior to termination by collecting two 0.25-m² quadrats of the aboveground rye biomass, cut at the soil surface, from each plot. To estimate N content of the aboveground rye, approximately 10 rye plants were randomly collected from the treatment plots, dried to a constant weight at 45°C for at least 72 h, and ground to pass through a 0.5 mm screen using a Wiley Mill (Thomas Scientific, Swedesboro, NJ). Total N concentration in plant tissues was determined by dry combustion using the Elementar Vario Max N/C Analyzer (Horneck and Miller, 1998) performed by the Pennsylvania State University Agricultural Analytical Services Laboratory (University Park, PA).

Rye managed as ryelage was harvested on 19 May 2014 and 22 May 2015 at Feekes growth stage 10.1 and 10.5 in 2014 and 2015, respectively. Plots were harvested with a small plot Carter harvester (Carter Mfg. Co., Inc., Brookston, IN), with one swath measuring 0.91-m wide. In 2014, just prior to ryeilage harvest, 10 rye plants were randomly collected in treatment plots, avoiding the yield strip area, for plant tissue N analysis to determine aboveground rye N content. Rye plant tissues were processed and analyzed as described previously for cover crop N concentrations. In 2014 a representative strip of rye, measuring 0.91 × 9.1 m, was harvested to determine yield. In 2015, the whole plot was harvested with the Carter harvester and a 500-g subsample from the harvested yield strips was collected to simulate silage production in the laboratory. Rye subsamples were dried to 60% moisture content, scaled in a plastic bag with vacuum to assure anoxic conditions for fermentation, and placed in an incubator at 30°C for at least 3 wk. Simulated silage samples were sent to Dairy One Laboratory (Ithaca, NY) for wet chemistry analysis to determine crude protein (CP). The CP values were then divided by 6.25 to estimate total plant N (AOAC International, 2000) and multiplied by dry matter yield to calculate total N uptake of the ryeage. Due to differing manure-N content applied EARLY and LATE, N content in aboveground biomass was used to calculate the N in above ground biomass as a percentage of the applied manure-N to compare the relative effects of the treatments on N uptake (%ManureN-R).

Corn was planted approximately 2 wk after ryeelage was harvested, across all treatments. In 2014, TA 514–28 (101-d relative maturity) was planted on 31 May 2014. In 2015, Channel 197–68STXRB (97-d relative maturity) was planted on 10 June 2015. In both years, corn was planted at a rate of 79,040 seeds ha⁻¹ using a John Deere 1780 no-till planter (Deere & Company, Moline, IL) on 76-cm row spacing. Starter fertilizer (10–20–20) was applied at 15 kg N ha⁻¹. Other than fall-applied manure and starter fertilizer, no additional fertilizer was applied to evaluate the experimental treatment effects on corn silage yields. Corn was harvested for silage with an Almaco SPC-40 (Almaco, Nevada, IA) small plot combine on 19 Sept. 2014 and 28 Sept. 2015 from two representative corn rows, measuring 1.91-m long, selected from the middle of each plot using a two-row corn harvester. Total harvested foraged was calculated from the sum of ryeelage and corn silage yields.

Ammonia–Nitrogen Measurement

After each manure application, ammonia gas was measured using an INNOVA 1412 photoacoustic gas monitor (AirTech Instruments A/S, Ballerup, Denmark). The photoacoustic gas monitor was connected to a 76 × 76 × 10 cm (L × W × H) chamber constructed from aluminum with a fan to recirculate air and was attached to a steel frame inserted approximately 3 cm into the soil. Chamber air was sampled once per minute for 4 min and NH₃ emission rate was calculated by a linear regression of change in NH₃ concentration per time. This method was found to underestimate NH₃ emission rates, so results are best used for relative comparisons among treatments (C. Dell, personal communication, 2014).

Ammonia was monitored shortly after manure application in a total of eight plots, four plots with BM or IM in September 2013 and November 2014. Due to precipitation events during manure application in November 2013 and September 2014, NH₃ measurements were only monitored in a total of six plots, three plots with BM or IM. Ammonia gas measurements were repeated at different time intervals following application (TaA), within the same plot. After an EARLY application, NH₃ measurements were taken within 30 min after application, and approximately 5 and 24 h after manure application. Due to precipitation events and cold temperatures during EARLY application in 2014, and LATE application in 2013 and 2014, NH₃ gas measurements were taken at different time intervals after
application, within one h of manure application and approximately 24 h after manure application.

Percent Manure–Nitrogen in Soil
Soil samples were collected in all treatments by block, before corn planting on 20–23 May 2014 and 3–5 June 2015. Deep soil cores were sampled in each plot to a depth of 90 cm using a Giddings hydraulic probe (Giddings, Ft. Collins, CO). In plots with BM, three soil cores were composited from four depths: 0–15 cm, 15–30 cm, 30–60 cm, and 60–90 cm. In plots with IM, soil was sampled at every 76.5 cm based on the method developed by Meinen et al. (2015), whom found that NO₃ concentrations across 76.5 cm were normally distributed with peak nitrate concentrations near the injection band. When the manure band location was unknown, five soil cores were collected perpendicular to the direction of manure application at 15.2 cm increments across the 76.5 cm distance between injection bands. When the manure bands were marked after LATE application, three soil cores were collected; (i) on the manure band, (ii) 15.2 cm from the band, and (iii) 30.5 cm from the band. Cores were separated by location from the injection band and the four depths previously mentioned. Soil was dried in a greenhouse that averaged between 23 and 27°C for at least 5 d and ground to 1 mm using a Dynacrush soil crusher mill (Custom Laboratory Equipment Inc, Holden, MO). All soil samples were analyzed for NO₃ using the Specific Ion Electrode method described by Griffin (1995) by the Pennsylvania State University Agricultural Analytical Services Laboratory (University Park, PA). Soil samples taken from multiple locations in plots with IM were analyzed separately and soil nitrate results were averaged. Differences in manure–N application rate between EARLY and LATE applications, were accounted for by calculating residual soil nitrate kg ha–1 as a percentage of total manure–N applied (%ManureN-S).

Late Manure Injection Damage to Planted Rye
The percentage of rye damage after a late injected manure application was assessed in April 2014, in RLI. In April 2015 the rye damage was assessed in both CLI and RLI. In each experimental plot, rye injury was measured in four random rows where the manure injector intersected a row of planted rye. This was done by measuring the length of the rows with injured plants divided by the total length of the plot (9.1 m). Additionally, the percentage of rye plants lost in the damaged row was rated visually. On average the manure injector intersected one out of every five rows of rye. Therefore, the average percentage of rye loss in each plot was estimated by multiplying the average proportion of the rows damaged by the average percentage of plants lost, multiplied by 1/5 rows.

Weather Conditions
In the 7 d following a manure application, no precipitation was recorded in 2013 after the early application and in 2014 after a late application. Precipitation events occurred during and the week following the LATE manure application in 2013 and the EARLY manure application in 2014, totaling 0.9 cm and 4.0 cm of precipitation, respectively (Fig. 1a and 1b). Average temperature for the 7 d after EARLY applications was 14.1 and 13.0°C in 2013 and 2014, respectively. After LATE applications, average temperature for the 7 d was –2.5 and –1.4°C in 2013 and 2014, respectively (Fig. 1a and 1b). Average monthly temperature and monthly total precipitation during the months of the experiment were relatively similar between years (Table 1), with the exception of May 2015 that was drier than 2014 and the 30-yr normal. Temperatures in January, February, and March were lower than the average normal temperatures and snowfall recorded in January 2014 did not melt until the following month (Table 1). Over the period of time between the LATE manure application in November and April, daily temperatures averaged below 10°C in both study years (Table 1).

Rye Growing Degree Days
Rye growing degree days (GDD) were used as an indicator of rye growth and development and were calculated by calculating the average of the maximum daily temperature (T_max) and the minimum daily temperature (T_min) and subtracting the base temperature (T_base) of 4.4°C, which is the minimum temperature threshold for physiological development (Nutterton, 1958; Mirsky et al., 2011). Cumulative GDD (Cum. GDD) is the total of Fall GDD, and Spring GDD, where spring was initiated on 1 March (Nutterton, 1958; Mirsky et al., 2011).

\[
GDD = \left(\frac{T_{\text{max}} - T_{\text{min}}}{2}\right) - T_{\text{base}}
\]

Partial Budget Analyses
A partial budget analyses was conducted to evaluate the potential profit difference of rye yields when manure was either broadcasted or injected after an EARLY and LATE application. Partial budgets were constructed using 2014 and 2015 rye silage yields. Prices for variable and fixed costs such as labor, fuel, tractors, equipment, and land were based on prices published in the 2013–2014 and 2015–2016 Penn State Agronomy Guide (Harper, 2013, 2015). The cost of custom hired manure applications was determined by a survey of commercial manure haulers in the central Pennsylvania region (R. Meinen, personal communication, 2016) that found the difference between BM and IM was approximately (US$) $25 ha–1. Rye silage prices were obtained from the Penn State Feed Price list, and forage prices averaged for the year were used to determine the price of feed Mg–1 (Alex Heipher Group, Incorporated, 2015). Partial budget analyses reflect changes in costs and feed prices in each year.

Data Analyses
Data were analyzed using the PROC Mixed procedure of SAS 9.4 (SAS Institute Inc., Cary, NC). To determine if the variance was similar between years, a two-sided F-test was performed to compare residuals from ammonia gas emission, rye biomass, %ManureN-R, %ManureN-S, corn yield, and total harvested biomass. When residuals did not differ at α = 0.01, data were pooled across years, and year was included in the model as a fixed effect. Additionally, %ManureN-S data were analyzed separately by soil depth and were square root transformed to meet ANOVA assumptions. Least-square means (LSMEANS) were then back-transformed and reported as weighted means. The SLICE of PROC MIXED statement is an analysis of simple or main effects; it was used to perform a partitioned F-test analysis of LSMEANS for interactions of the main effects. Differences were considered significant when P < 0.05.
The two-sided F-test indicated that variance for ammonia gas data differed significantly between years, and so years were analyzed separately. Ammonia gas was measured multiple times after application and data were analyzed with repeated measures. The time of NH₃ sampling after manure application (TaA) was qualified sequentially as the first, second, or third measurement taken, and included in the model as fixed effects along with MoMA, ToMA, and interactions. Means were separated by Tukey’s LSMEANS test and identified as statistically significant when $P < 0.05$.

Rye biomass, %ManureN-R, %ManureN-S, corn yield, and total ryelage and corn silage harvested biomass data were pooled across years. Data were analyzed with each main factor (CM, MoMA, and ToMA) and all the interactions included in the model as fixed effects. Replicated blocks were nested in year and treated as a random effect as well as the interactions of blocks with main effects.

**RESULTS**

**Ammonia Volatilization**

In both years, the interaction of MoMA × TaA was significant ($P < 0.006$ and $P < 0.01$ in 2013 and 2014, respectively). In September 2013, the greatest amount of NH₃ gas was measured within 30 min of BM and was 14-fold higher than IM (Fig. 2a). After 5 and 24 h, ammonia gas losses did not differ between BM and IM (Fig. 2a). In November 2013, no NH₃ gases were detected after BM or IM (Fig. 2b).

In 2014, NH₃ gas loss did not differ between EARLY and LATE (Fig. 2c and 2d). The greatest NH₃ losses in 2014 occurred shortly after BM, when NH₃ losses were almost eight-fold and 88-fold higher than IM at EARLY and LATE, respectively (Fig. 2c and 2d). Similar to 2013, NH₃ losses in BM treatments decreased as TaA increased (Fig. 2a, 2c, and 2d).
24 h and 26 h after manure application, there were no differences in NH₃ gas losses between BM and IM treatments.

**Rye Biomass, Percentage of Manure–Nitrogen in Aboveground Rye, and Damage**

In the analysis of rye biomass, the main effect of year (P < 0.001) and the interaction of CM × MoMA × ToMA (P < 0.05) were significant. In the analysis of %ManureN-R, the interaction of year × CM × MoMA × ToMA (P < 0.05) was significant. On average, ryelage biomass was three times the rye cover crop biomass in 2014, and over four times in 2015. Similarly, in 2014 and 2015, the %ManureN-R in ryelage biomass was 1.9-fold larger (average of 45 vs. 24%) and 3.3-fold greater (average of 66 vs. 18%) than in the rye cover crop (Table 2).

In both years, for rye cover crop there were no significant effects of MoMA on biomass or the %ManureN-R, and ToMA only differed in 2014 for BM, when the CLB had 61% greater %ManureN-R than the CEB (Table 2).

By contrast, for ryelage, MoMA resulted in several biomass and %ManureN-R differences. Ryelage biomass was 46% larger in REI than REB in 2014, and 36% larger in 2015 (Table 2). Similarly, manure injection resulted in greater ryelage %ManureN-R than BM in both years when applied EARLY (61 and 50% in 2014 and 2015, respectively), and LATE (15 and 76% in 2014 and 2015, respectively).

Time of manure application also resulted in several biomass and %ManureN-R differences in ryelage. Late manure application in ryelage increased %ManureN-R in both years whether it was broadcast or injected. However, rye stands were damaged following LATE IM and resulted in 4 and 11% loss in 2014 and 2015, respectively. Additionally, damage was significantly greater in 2015 than 2014 (P < 0.001).
In 2014, ryelage biomass was 25% larger and %ManureN-R was 86% larger in RLB compared to REB, and RLI %ManureN-R was 60%, which was 33% greater than REI (Table 2). In 2015, RLB increased ryelage %ManureN-R by 44% compared to REB, and RLI %ManureN-R averaged 91% (Table 2), which was 69% larger than REI %ManureN-R (at 54%), even though rye biomass was 22% smaller in RLI compared to REI (Table 2). Late-injected ryelage was the combination of three factors that resulted in the highest %ManureN-R within each year 2014 (60%) and 2015 (91%), respectively.

Percentage of Manure Nitrogen in Soil

Prior to corn planting, the back-transformed mean percentage of manure–N measured in the soil as NO3 (%ManureN-S) ranged from 2.1 to 29.8% (Table 3). There were several significant two-way and three-way interactions of the main effects for %ManureN-S at 0–15 and 15–30 cm soil depths (Table 3). While at the 30–60 cm depth, the only significant interaction for %ManureN-S was year × CM; and at 60–90 cm depth, year × ToMA (Table 3).

In 2014, the %ManureN-S in IM treatments did not differ between CM for any depth except at 0–15 cm, when %ManureN-S was 69% larger in CEI than REI. However, in 2015, %ManureN-S was greater where rye was managed as a cover crop than ryelage at all depths except in EARLY IM treatments at 15–30 cm and for all MoMA × ToMA interactions at 60–90 cm (Table 3, Fig. 3). Cover crops with BM also had greater %ManureN-S compared to ryelage in the top three soil depths (0–60 cm) with EARLY BM increases of 82, 90, and 77% at 0–15, 15–30, and 30–60 cm depths, respectively; and LATE BM increases of 88, 58, and 94% at 0–15, 15–30, and 60–90 cm depths, respectively, in 2015 (Table 3, Fig. 3). In 2014, CLI %ManureN-S means were large relative to the other %ManureN-S means in the 0–15, 15–30, and 30–60 cm depths (Table 3, Fig. 3); and compared to RLI, CLI %ManureN-S at the top three soils depths were 2.3-fold, 3.6-fold, and 1.6-fold larger, respectively. Early-injected cover crop %ManureN-S compared to REI were also 1.9-fold greater at both 0–15 and 30–60 cm depths, respectively. At all soil depths in 2014, %ManureN-S was greater in cover crops with IM than BM. The EARLY %ManureN-S ranged from 64–110% greater in CEI than CEB, and the LATE %ManureN-S ranged from 70–178% greater in CLB than RLB at three of four soil depths. In ryelage, IM also increased the %ManureN-S when applied EARLY by 98% at 60–90 cm, and when applied LATE by 46% at 0–15 cm (Table 3, Fig. 3). In 2015, %ManureN-S was greater in CEI than CEB only at

Table 2. Rye dry matter biomass and percent of manure–N in aboveground rye biomass (%ManureN-R) measured in 2014 and 2015 where SLICE of PROC MIXED statement was used to determine the main effect of crop management (CM), method of manure application (MoMA), and time of manure (ToMA) by performing a partitioned F-test analysis of LSMEANS of the interaction of year × CM × MoMA × ToMA.

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Aboveground rye biomass</th>
<th>%ManureN-R</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2014</td>
<td>2015</td>
</tr>
<tr>
<td>Cover crop, early broadcasted (CEB)</td>
<td>1.9a†A‡</td>
<td>1.0aA</td>
</tr>
<tr>
<td>Cover crop, early injected (CEI)</td>
<td>2.0bA</td>
<td>0.9 aA</td>
</tr>
<tr>
<td>Cover crop, late broadcasted (CLB)</td>
<td>1.9aA</td>
<td>1.0aA</td>
</tr>
<tr>
<td>Cover crop, late injected (CLI)</td>
<td>1.6aA</td>
<td>0.7aA</td>
</tr>
<tr>
<td>Ryelage, early broadcasted (REB)</td>
<td>3.9bB</td>
<td>3.3bA</td>
</tr>
<tr>
<td>Ryelage, early injected (REI)</td>
<td>5.7aA</td>
<td>4.5aA</td>
</tr>
<tr>
<td>Ryelage, late broadcasted (RLB)</td>
<td>4.8aA</td>
<td>3.8aA</td>
</tr>
<tr>
<td>Ryelage, late injected (RLI)</td>
<td>5.4aA</td>
<td>3.5aB</td>
</tr>
</tbody>
</table>

SLICE tests

Effect of CM

CEB vs. REB *** *** *** ***
CLB vs. RLB *** *** *** ***
CEI vs. REI *** *** *** ***
CLI vs. RLI *** *** *** ***

Effect of MoMA

CEB vs. CEI NS§ NS NS NS
CLB vs. CLI NS NS NS NS
REB vs. REI *** *** NS ***
RLB vs. RLI NS NS *` NS

Effect of ToMA

CEB vs. CLB NS NS NS ** NS
CEI vs. CLI NS NS NS NS
REB vs. RLB ** NS *** NS
REI vs. RLI NS *** *** ***

§ NS, nonsignificant.

† Different lowercase letters (a, b) indicate MoMA that differ within the same CM and ToMA at P < 0.05 according to the ‘SLICE’ procedure.

‡ Different uppercase letters (A, B) indicate ToMA that differ within the same rye CM and MoMA at P < 0.05 according to the ‘SLICE’ procedure.

* Significant at the P < 0.05 level.
** Significant at the P < 0.01 level
*** Significant at the P < 0.001 level.
0–15 cm by 69% and at 30–60 cm by 55%. In the top three soil depths, \%ManureN-S ranged from 1.6 to 3.9-fold greater in CLI than CLB (Table 3). In 2015, RLI %ManureN-S was greater than RLB at all soil depths, ranging from 5.5-fold greater at 0–15 cm, to three-fold greater at 15–30 and 30–60, and two-fold greater at 60–90 cm (Table 3, Fig. 3).

Partial Budget Analyses

Ryelage yields and the cost of custom hired manure applications determined differences in net income between BM and IM. Although IM cost $25 ha\(^{-1}\) more than BM, larger ryelage yields after EARLY IM in 2014 and 2015 than EARLY BM resulted in greatest sale revenues (Tables 3, 5). In 2014 across EARLY and LATE applications, net income after IM averaged $258.70 ha\(^{-1}\) greater than after BM (Table 4). In 2015, after an EARLY application, net income was $288.80 ha\(^{-1}\) greater for IM than BM (Table 4). However, the LATE IM application in 2015 damaged rye, reduced yields, and resulted in net income that was $103.30 ha\(^{-1}\) smaller in RLI than RLB (Tables 2, 4). Further, net return was $261.20 ha\(^{-1}\) greater after REI than RLI (Table 4).

**Table 3. Percentage of manure-N remaining in the soil as NO\(_3\) (%ManureN-S) in 2014 and 2015 where SLICE of PROC MIXED statement was used to determine the main effect of crop management (CM), manure application method (MoMA), and manure application time (ToMA) by performing a partitioned F-test analysis of LSMEANS of the interaction of year \(\times\) CM \(\times\) MoMA \(\times\) ToMA.

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Soil depth cm</th>
<th>0–15</th>
<th>15–30</th>
<th>30–60</th>
<th>60–90</th>
<th>0–15</th>
<th>15–30</th>
<th>30–60</th>
<th>60–90</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cover crop, early broadcasted (CEB)</td>
<td>2014</td>
<td>4.3b†</td>
<td>3.5bB</td>
<td>5.3bA</td>
<td>5.3bA</td>
<td>4.3bB</td>
<td>3.9aA</td>
<td>8.5bA</td>
<td>9.7aA</td>
</tr>
<tr>
<td>Cover crop, early injected (CEI)</td>
<td>2015</td>
<td>7.3aB</td>
<td>5.8aA</td>
<td>10.4aA</td>
<td>11.1aB</td>
<td>7.3aB</td>
<td>4.3aB</td>
<td>13.2aB</td>
<td>11.8aA</td>
</tr>
<tr>
<td>Cover crop, late broadcasted (CLB)</td>
<td>2014</td>
<td>7.3bA</td>
<td>6.3aA</td>
<td>7.9bA</td>
<td>6.8aB</td>
<td>9.1bA</td>
<td>5.8bA</td>
<td>13.2aB</td>
<td>7.9aA</td>
</tr>
<tr>
<td>Cover crop, late injected (CLI)</td>
<td>2015</td>
<td>12.5aA</td>
<td>7.9aA</td>
<td>14.7aA</td>
<td>18.9aA</td>
<td>29.8aA</td>
<td>22.5aA</td>
<td>21.6aA</td>
<td>11.1aA</td>
</tr>
<tr>
<td>Ryelage, early broadcasted (REB)</td>
<td>2014</td>
<td>3.1aB</td>
<td>3.5aB</td>
<td>5.8aA</td>
<td>5.3bB</td>
<td>2.4aA</td>
<td>2.1aA</td>
<td>4.8aA</td>
<td>6.3aA</td>
</tr>
<tr>
<td>Ryelage, early injected (REI)</td>
<td>2015</td>
<td>4.3aB</td>
<td>5.3aA</td>
<td>8.5aB</td>
<td>10.4aA</td>
<td>3.9bA</td>
<td>2.8aB</td>
<td>6.8aB</td>
<td>9.1aA</td>
</tr>
<tr>
<td>Ryelage, late broadcasted (RLB)</td>
<td>2014</td>
<td>6.3bA</td>
<td>6.8aA</td>
<td>9.1bA</td>
<td>11.1aA</td>
<td>2.4bA</td>
<td>2.1bA</td>
<td>4.8bA</td>
<td>5.3bA</td>
</tr>
<tr>
<td>Ryelage, late injected (RLI)</td>
<td>2015</td>
<td>9.1aA</td>
<td>6.8aA</td>
<td>15.5aA</td>
<td>15.5aA</td>
<td>13.2aA</td>
<td>6.3aA</td>
<td>13.2aA</td>
<td>12.5aA</td>
</tr>
</tbody>
</table>

**SLICE procedure**

**Effect of CM**

<table>
<thead>
<tr>
<th>Treatment</th>
<th>2014</th>
<th>2015</th>
</tr>
</thead>
<tbody>
<tr>
<td>CEB vs. REB</td>
<td>NS§</td>
<td>NS §</td>
</tr>
<tr>
<td>CLB vs. RLB</td>
<td>NS</td>
<td>NS</td>
</tr>
<tr>
<td>CEI vs. REI</td>
<td>*</td>
<td>NS</td>
</tr>
<tr>
<td>CLI vs. RLI</td>
<td>NS</td>
<td>NS</td>
</tr>
</tbody>
</table>

**Effect of MoMA**

<table>
<thead>
<tr>
<th>Treatment</th>
<th>2014</th>
<th>2015</th>
</tr>
</thead>
<tbody>
<tr>
<td>CEB vs. CEI</td>
<td>*</td>
<td>NS</td>
</tr>
<tr>
<td>CLB vs. CLI</td>
<td>**</td>
<td>NS</td>
</tr>
<tr>
<td>REB vs. REI</td>
<td>NS</td>
<td>NS</td>
</tr>
<tr>
<td>RLB vs. RL</td>
<td>*</td>
<td>NS</td>
</tr>
</tbody>
</table>

**Effect of ToMA**

<table>
<thead>
<tr>
<th>Treatment</th>
<th>2014</th>
<th>2015</th>
</tr>
</thead>
<tbody>
<tr>
<td>CEB vs. CLB</td>
<td>*</td>
<td>NS</td>
</tr>
<tr>
<td>CEI vs. CLI</td>
<td>**</td>
<td>NS</td>
</tr>
<tr>
<td>REB vs. RLB</td>
<td>*</td>
<td>**</td>
</tr>
<tr>
<td>REI vs. RLI</td>
<td>***</td>
<td>NS</td>
</tr>
</tbody>
</table>

† Different lowercase letters (a, b) indicate MoMA that differ within the same rye CM and ToMA at \( P < 0.05 \) according to the ‘SLICE’ procedure.

‡ Different uppercase letters (A, B) indicate ToMA that differ within the same rye CM and MoMA at \( P < 0.05 \) according to the ‘SLICE’ procedure.

§ NS, nonsignificant.

0–15 cm by 69% and at 30–60 cm by 55%. In the top three soil depths, %Manure-N-S ranged from 1.6 to 3.9-fold greater in CLI than CLB (Table 3). In 2015, RLI %Manure-N-S was greater than RLB at all soil depths, ranging from 5.5-fold greater at 0–15 cm, to three-fold greater at 15–30 and 30–60, and two-fold greater at 60–90 cm (Table 3, Fig. 3).

Late manure applications also resulted in greater %Manure-N-S than EARLY in both years. In 2014, most of the significant increases of %Manure-N-S were in BM with cover crops ranging from 69 to 79% greater, and in ryelage from 82 to 110% greater than EARLY (Table 3, Fig. 3). In 2015, %Manure-N-S in CLB was only larger than CEB at 0–15 cm. By contrast, in 2015, %Manure-N-S was larger in CLI than CEI at the top three soil depths ranging from 5.2-fold at 15–30 cm to 1.6-fold greater at 30–60 cm. Similarly, %Manure-N-S was greater in RLI than REI at the top three soil depths, ranging from 3.4-fold at 0–15 cm to 1.9-fold greater at 30–60 cm (Table 3, Fig. 3).

**Corn Silage Yields**

In the analysis of corn silage yields, the two-way interactions of CM \( \times \) ToMA \( ( P < 0.006) \) and year \( \times \) MoMA \( ( P < 0.03) \) were significant. Across years, corn silage yields with rye cover compared to with ryelage were 28% greater with LATE applications (Table 5). Following EARLY manure applications, corn

0–15 cm by 69% and at 30–60 cm by 55%. In the top three soil depths, %Manure-N-S ranged from 1.6 to 3.9-fold greater in CLI than CLB (Table 3). In 2015, RLI %Manure-N-S was greater than RLB at all soil depths, ranging from 5.5-fold greater at 0–15 cm, to three-fold greater at 15–30 and 30–60, and two-fold greater at 60–90 cm (Table 3, Fig. 3).

Late manure applications also resulted in greater %Manure-N-S than EARLY in both years. In 2014, most of the significant increases of %Manure-N-S were in BM with cover crops ranging from 69 to 79% greater, and in ryelage from 82 to 110% greater than EARLY (Table 3, Fig. 3). In 2015, %Manure-N-S in CLB was only larger than CEB at 0–15 cm. By contrast, in 2015, %Manure-N-S was larger in CLI than CEI at the top three soil depths ranging from 5.2-fold at 15–30 cm to 1.6-fold greater at 30–60 cm. Similarly, %Manure-N-S was greater in RLI than REI at the top three soil depths, ranging from 3.4-fold at 0–15 cm to 1.9-fold greater at 30–60 cm (Table 3, Fig. 3).

**Partial Budget Analyses**

Ryelage yields and the cost of custom hired manure applications determined differences in net income between BM and IM. Although IM cost $25 ha\(^{-1}\) more than BM, larger ryelage yields after EARLY IM in 2014 and 2015 than EARLY BM resulted in greatest sale revenues (Tables 3, 5). In 2014 across EARLY and LATE applications, net income after IM averaged $258.70 ha\(^{-1}\) greater than after BM (Table 4). In 2015, after an EARLY application, net income was $288.80 ha\(^{-1}\) greater for IM than BM (Table 4). However, the LATE IM application in 2015 damaged rye, reduced yields, and resulted in net income that was $103.30 ha\(^{-1}\) smaller in RLI than RLB (Tables 2, 4). Further, net return was $261.20 ha\(^{-1}\) greater after REI than RLI (Table 4).
silage yields were only greater by 17% in CEI than REI in 2014, and by 19% greater in CEB than REB in 2015 (Table 5).

The effect of MoMA on corn silage yields was significant for all treatments in 2015, but not in 2014 (Table 5). In 2014, following cover crops, corn silage yields were 19% greater in IM than BM (Table 5). Following ryelage, in 2014, corn yield was 30% greater in LATE IM than LATE BM but did not differ in EARLY IM from EARLY BM (Table 5). In 2015, following both rye cover and ryelage, corn silage yields averaged 31% greater in IM than BM.

The effect of ToMA only affected corn silage yields when rye was managed as rye cover. After rye cover, corn silage yields averaged 21% greater with LATE IM compared to EARLY IM across both years. Following BM, corn silage yield was 19% greater after LATE than EARLY in 2015 only (Table 5).

**Total Harvested Forage**

Crop management significantly influenced rye biomass, %ManureN-R, %ManureN-S in 2015, and corn silage and total forage harvested yield in most treatment combinations (Tables 2, 3). Across all treatments and years, total harvested forage averaged 20% greater with IM compared to BM treatments. Time of manure application did not affect total harvested forage in ryelage-corn treatments nor rye cover-corn EARLY BM. But total forage produced in CEI compared to CLI averaged 21% greater across years (Table 5).

**DISCUSSION**

In the literature, studies have documented the environmental benefits of a rye cover crop (Tonitto et al., 2006; Martinez-Feria et al., 2016) and ryelage (Krueger et al., 2012), significant N conservation benefits of newer manure application technologies such as the shallow disc injectors (Maguire et al., 2011; Dell et al., 2011, 2012; Duncan et al., 2017; Bierer et al., 2017), and some have investigated the integration of IM with cover crops (Singer et al., 2008; Cambardella et al., 2010). However, evaluation of multiple fall manure management strategies coupled with a rye cover crop or ryelage is lacking in the literature. In this study, we compared factorial combinations of winter rye CM, MoMA, and ToMA to determine management strategies that have the potential to reduce environmental N losses and conserve N for crop utilization.

**Rye Management Impacts**

Crop management significantly influenced rye biomass, %ManureN-R, %ManureN-S in 2015, and corn silage and total forage harvested yield in most treatment combinations (Tables 2,
Table 4. Partial budget comparison of ryelage production in 2014 and 2015 that received a broadcasted (BM) or injected (IM) manure application in September (EARLY) or November (LATE).

<table>
<thead>
<tr>
<th>Rye silage yields†</th>
<th>2014</th>
<th></th>
<th>2015</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>EARLY BM</td>
<td>IM BM</td>
<td>LATE BM</td>
<td>IM BM</td>
</tr>
<tr>
<td>Average yield</td>
<td>3.9</td>
<td>5.9</td>
<td>4.8</td>
<td>5.4</td>
</tr>
<tr>
<td>Gross income (US$)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sale revenue (US$)</td>
<td>921.20</td>
<td>1346.30</td>
<td>1133.80</td>
<td>1275.50</td>
</tr>
<tr>
<td>Input costs</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Manure application</td>
<td>50.20</td>
<td>74.90</td>
<td>50.20</td>
<td>74.90</td>
</tr>
<tr>
<td>Other fixed and variable costs</td>
<td>336.40</td>
<td>336.40</td>
<td>336.40</td>
<td>336.40</td>
</tr>
<tr>
<td>Total input costs</td>
<td>386.60</td>
<td>411.30</td>
<td>386.60</td>
<td>411.30</td>
</tr>
<tr>
<td>Net income</td>
<td>534.60</td>
<td>935.00</td>
<td>747.20</td>
<td>864.20</td>
</tr>
</tbody>
</table>

† Average ryelage yields at 100% dry matter.

3, and 5). Compared to the ry cover crop, ryelage biomass was 3 to 4.2-fold greater and %ManureN-R was 1.9 to 3.2-fold larger in the aboveground ryelage biomass (Table 2). Although the number of calendar days between cover crop termination and ryelage harvest was similar each year (10 or 11 d in 2014 and 2015, respectively), 15 more GDD days (130 vs. 115 GDD, or 14%) accumulated in 2015. This may explain of the larger increases in 2015 in ryelage biomass and %ManureN-R. Others have also reported similar increases in rye biomass with relatively short time delays in termination time (Wagger, 1989; Clark et al., 1997; Duiker and Curran, 2005; Mirskey et al., 1921; Komatsuzaki and Wagger, 2015).

Extending rye growth for ryelage also appears to have increased rye soil N-scavenging capabilities. In 2014, %ManureN-S was 69% greater in cover crop rye than ryelage EARLY injected at the 0–15cm depth, and in 2015 %ManureN-S was larger in cover crop than ryelage in all treatments at multiple depths with a range from 58% to 3.6-fold increase (Table 3). The 14% greater GDD accumulation for ryelage after cover crop termination in 2015 than in 2014, as well as factors such as precipitation and leaching, may have contributed to the smaller %ManureN-S in ryelage soil compared to cover crop in 2015. Komatsuzaki and Wagger (2015) also found that when rye termination was delayed in spring, rye aboveground biomass and N content were increased, and soil NO3–N was reduced. They attributed the reduced soil NO3–N to rye spring growth and soil N scavenging. Similarly, Heggenstaller et al. (2008) compared winter annuals double-cropped with corn to a sole corn crop and found that total dry matter yields and total crop N uptake were greater with the double-crop system, and leachable soil N was significantly reduced.

The 58% to 3.6-fold increase in %ManureN-S in cover crop compared to ryelage in all treatments at multiple depths in 2015 (Table 3) possibly contributed to the greater corn silage yields after cover crop than ryelage for all treatments except EARLY inject (Table 5). By contrast, in 2014, the few %ManureN-S differences between depths and treatments, did not correlate with the pattern of greater corn silage yields after rye cover crop than ryelage for most of the manure management treatments (Tables 3 and 5). Exceptionally dry May weather in 2015 (Table 1) may have limited N leaching until corn plants were established and able to take up %ManureN-S compared to the wetter spring of 2014, when rainfall was evenly and adequately distributed throughout the corn growing season (Table 1).

Increased N removal and total forage production when harvesting ryelage could be advantageous for dairy farmers whom are subject to water quality regulations and have limited arable land to apply manure. Despite potential benefits, some farmers may be apprehensive about adopting this practice due to concerns about the negative impact of winter cereal crops on corn production and yield (Ketterings et al., 2015b). Some other studies have also reported that double cropped small grains reduced subsequent corn yield (Krueger et al., 2011; Tollenaar et al., 1992). In a 2-yr study where no additional N was supplied for corn production, harvesting rye before corn reduced soil moisture and resulted in an average of 23% reduction in corn yield compared to sole-cropped corn (Krueger et al., 2011). However, total harvested biomass did not differ significantly between the sole-cropped corn and the winter annual rye followed by corn treatments (Krueger et al., 2011).

In this study, corn silage yields were lower following ryelage than a cover crop depending on MoMA, ToMA, and year (Table 5). However, to assess manure-N availability after the winter annual, we did not apply additional N to corn in any of the treatments. While harvesting ryelage versus terminating it earlier as a cover crop may reduce corn silage yields, supplementing with N for the economic optimum would likely change corn yield differences, total harvested forage production, and net profitability. Further, we found that total harvested forage was 27% greater in ryelage-corn treatments than rye cover–corn treatments in all treatments in 2014, and in 23% greater with EARLY manure applications in 2015. In 2015, total harvested forage did not differ, when manure was applied LATE and also 10 d after rye was replanted and more rye plants were damaged in the LATE IM than the previous year.

Manure Management Impacts with Ryelage

Significant interactions of CM with MoMA and ToMA in this study revealed opportunities to reduce N losses, and increase ryelage biomass, %ManureN-R, %ManureN-S, corn silage yields, and total harvested forage. In both years, ryelage biomass and %ManureN-R were higher in REI than REB. After EARLY applications, temperatures were above 10°C in both years and initial NH4 losses were greater after BM than IM (Fig. 1 and 2a, 2c). Immediate incorporation with shallow disc manure injection reduced NH4 volatilization EARLY when fall temperatures were relatively warm (Fig. 2a and 2c). Others have also reported that IM increased crop yield and crop N content compared to BM in
wheat (Nyord et al., 2012; Gonzatto et al., 2017), corn (Gonzatto et al., 2017), and perennial grasses (Huijsmans et al., 2016).

Despite the higher input cost associated with IM, larger ryelage yields in REI resulted in greater net returns than in REB (Tables 2 and 4). Following ryelage, %ManureN-S did not differ between REB and REI in either year at most depths, with the exception at the 60–90 cm depth in 2014 (Table 3). While more manure–N was taken up by aboveground ryelage in REI than REB, the 98% higher %ManureN-S at 60–90 cm soil depth in 2014 suggests there is potential for nitrate leaching.

Differences in corn silage yields and total harvested forage indicated a benefit of EARLY IM compared to EARLY BM. With limited N inputs from only fall manure and corn starter fertilizer, corn silage yield following EARLY IM was 35% larger than EARLY BM in 2015, and total harvested forage averaged 26% greater than EARLY BM across years (Table 5). While more manure–N was taken up by aboveground ryelage in REI than REB, the 98% higher %ManureN-S at 60–90 cm soil depth in 2014 suggests there is potential for nitrate leaching.

Differences in corn silage yields and total harvested forage indicated a benefit of EARLY 1M compared to EARLY BM. With limited N inputs from only fall manure and corn starter fertilizer, corn silage yield following EARLY IM was 35% larger than EARLY BM in 2015, and total harvested forage averaged 26% greater than EARLY BM across years (Table 5). In 2014, corn silage yields did not differ between EARLY IM and BM. However, ryelage biomass was 46% greater in EARLY IM compared to BM and contributed to greater total harvested forage with ryelage EARLY IM versus EARLY BM.

Following LATE applications, MoMA did not affect ryelage biomass, however %ManureN-R was greater in RLI than RLB (Table 2). Initial ammonia losses in fall 2014, were higher in RLB than RLI (Fig. 2d), and NH₃ volatilization losses after N applications can occur in winter, even though cold temperatures can reduce NH₃ losses (Sommer et al., 1991; Engel et al., 2011). Nitrogen runoff along with volatilization losses after LATE BM also may have contributed to the higher ryelage %ManureN-R in LATE IM. In 2015, when rye was replanted 10 d prior to the late manure application date, more plants were damaged in LATE IM than in 2014. The reduced rye stands could have led to fewer plants competing for and taking up soil N, contributing to higher %ManureN-R. Similarly, Blonski et al. (2004) found that IM increased N content in perennial grass but not crude protein yield, which they attributed to plant damage.

Injecting manure into an established crop can damage stands by pruning roots, creating anaerobic and toxic conditions in the manure bands, compacting or fracturing the soil, and drying the soil surface layers (Van Der Meer et al., 1987; Rees et al., 1993; Webb et al., 2010). Extent of damage can vary with the crop growth stage, as well as the depth and width of the cut made by the injector, weather, and soil conditions (Webb et al., 2010). In 2015, IM plant damage resulted in $103 ha⁻¹ reduced returns compared to LATE BM (Table 4). Despite the reduced ryelage yield in 2015, the subsequent corn silage yield was 35% greater
and the total forage produced from ryelage and corn silage was 23% larger in the LATE IM compared to LATE BM (Table 5).

In both years, %ManureN-S was greater at multiple soil depths in RLI than RLB (Table 3, Fig. 3). Figure 3 illustrates that in RLI and CLI more NO₃⁻N may have moved deeper in the soil by spring in 2014 than in 2015. The 15.6 cm of more precipitation between the LATE application and spring soil sampling in 2014 than in 2015 (39.6 vs. 24 cm, data not shown) may have contributed to more NO₃⁻N moving deeper into the soil profile. Following the larger %ManureN-S at multiple soil depths in spring, subsequent corn silage yields were on average 33% greater after both rye cover and ryelage crops in LATE IM than BM in both years (Table 5), suggesting the subsequent corn crop utilized some of the greater %ManureN-S.

And although ryelage biomass did not differ with MoMA following LATE applications, greater corn silage yields following LATE IM versus LATE BM contributed to an average 21% greater total harvested forage in LATE IM than LATE BM (Table 5). If ryelage and corn yields were to be optimized, lower fertilizer inputs might be required after LATE IM than LATE BM and EARLY IM than EARLY BM (Table 5).

As we hypothesized, IM could have reduced NH₃ volatilization and manure run-off after the LATE application, and cooler temperatures and shorter daylengths could have also reduced soil N mineralization in fall, conserving more N for spring mineralization. These factors may have contributed to the significantly increased %ManureN-R, greater %ManureN-S at multiple depths, greater corn silage yields, and greater total harvested forage in RLI compared to RLB (Tables 2, 3, 5, and Fig. 3). Others have reported that manure applied in late versus early fall resulted in smaller flow-weighted NO₃⁻N concentrations in tile-drainage during the subsequent spring (van Es et al., 2006) or less soil NO₃⁻N at deep soil depths (31–60 cm and 61–90 cm) in spring (Vetsch et al., 2017) suggesting reduced risk of NO₃⁻N leaching. In addition, Bork et al. (2013) found that soil mineral N (NO₃⁻ and NH₃) was increased by 35% when liquid hog manure was injected compared to surface applied on a perennial native grass-soil NO3–N by 23% in a clay loam and 110% in a sandy loam.

In both years, LATE applications significantly increased %ManureN-R in ryelage compared to EARLY IM applications with BM or IM (33–86%, Table 2). In 2013, low air temperatures and precipitation during the subsequent spring (van Es et al., 2006) or less soil NO₃⁻N at deep soil depths (31–60 cm and 61–90 cm) in spring (Vetsch et al., 2017) suggesting reduced risk of NO₃⁻N leaching. In addition, Bork et al. (2013) found that soil mineral N (NO₃⁻ and NH₃) was increased by 35% when liquid hog manure was injected compared to surface applied on a perennial native grass-soil NO₃⁻N by 23% in a clay loam and 110% in a sandy loam.

In both years, %ManureN-S was greater at multiple soil depths in ryelage compared to LATE IM in Table 3, Fig. 3). However, this did not result in greater corn silage or total forage harvested yields (Table 5) suggesting the potential more soil N leaching from the LATE IM compared to EARLY ryelage treatments.

**Manure Management Impacts with Rye Cover Crop**

When rye was managed as a cover crop, the manure application method and timing practices (MoMA and ToMA) that reduced N losses and conserved N in the rye cover crop, the soil, and for affected the subsequent corn crop were similar to those after ryelage, with the exception of LATE IM, which increased corn silage yield following rye cover, but not ryelage. In both years, %ManureN-S was greater in CEI than CEB at multiple depths, (67% in 2014 at the two shallow depths, and 69% greater at the 0–15 cm depth in 2015, Table 3, Fig. 3), likely due to reduced NH₃ losses associated with immediate manure incorporation of EARLY IM. Similarly, following a LATE application, %ManureN-S was 70% greater in CLI than CLB at 0–15 cm depth in 2014, and averaged 259% greater at the two shallow depths in 2015 (Table 3, Fig. 3). Subsequent corn silage yields benefited from IM compared to BM, averaging 19% greater in 2014 and 27% greater in 2015 (Table 5), which might reduce fertilizer inputs if corn silage were managed for optimum yields. There is a lack of literature comparing the effect of fall manure injection to surface broadcast with rye cover or ryelage, and their impact on a subsequent crop. However, in Mississippi, Tewolde et al. (2015) found that cotton lint yield was greater following subsurface banding of fall-applied poultry litter to a winter wheat cover crop compared to no cover crop.

Others have found that combining rye-oat cover crops with manure injection compared to without manure or without a cover crop in Iowa, increased cover crop N uptake, reduced soil NO₃⁻N, and did not negatively affect subsequent corn yield (Singer et al., 2008; Cambardella et al., 2010). Multiple factors may explain the lack of a corn yield response following a rye cover crop, including a shorter fall time period in the Midwest after corn grain for the cover crop to grow and capture manure-N compared to the Northeast (Grabber et al., 2014, Miguez and Bollero, 2005), as well as a high C/N ratio of the terminated rye cover crop that can immobilize N (Clark et al., 1997; McSwiney et al., 2010), allelopathy, reduced corn populations, and reduced soil temperature and moisture (Duiker and Curran, 2005; Kaspar and Bakker, 2015; Ketterings et al., 2015a; Martinez-Feria et al., 2016). Management practices that have been reported to alleviate potential negative rye cover crop effects on subsequent corn yield include (i) terminating a cover crop at relatively early stages of growth; (ii) delaying corn planting approximately 10 d to 2 or 3 wk after rye termination to allow the rye biomass to decompose and reduce the risk of N immobilization, allelopathy, soil cooling and moisture reduction, and rye residue planter interference; and (iii) applying additional N fertilizer (Duiker and Curran, 2005; Ketterings et al., 2015a; Martinez-Feria et al., 2016; Snapp and Suraput, 2018). In addition to the greater %ManureN-R that rye cover removed, some of these effects associated with longer rye growth likely contributed to the lower corn silage yields that we measured following ryelage treatments compared to rye cover crop treatments (Table 5).

Although N was available in the soil to benefit the corn, greater %ManureN-S at deeper soil depths suggests N could also be lost via leaching, since %ManureN-S was on average 99% higher in CEI than CEB in 2014 across the 30–60 and 60–90 cm depths, 55% higher in CEI than CEB in 2015, at the 30–60 cm depth; on average 132% higher in CLI than CLB in 2014 across 30–60
and 60–90 cm depths; and 64% higher in CLI than CLB in 2015 at the 30–60 cm depth (Table 3, Fig. 3). Dell et al. (2012) found that spring shallow disc injection prior to corn effectively reduced ammonia losses without increasing N leaching, however, after fall manure applications in the northeast, winter annual crop growth and N uptake may be limited in the fall.

Delaying manure applications in rye cover treatments until LATE versus EARLY also conserved manure-N for rye or subsequent corn silage. When manure was LATE broadcasted, %ManureN-R was 61% greater in CLB than CEB (Table 2), and %ManureN-S averaged 74% greater in CLB than CEB across the two shallowest depths in 2014. In 2015, %ManureN-S was 110% greater at the 0–15 cm depth in CLB than CEB, which may have contributed to 19% greater corn silage yield in CLB than CEB and took up more manure–N than cover crops. Without supplementation of manure–N in ryelage, corn silage yields did not differ with time of application, but manure–N in ryelage was greater with LATE IM than EARLY IM.

Overall, LATE applications can offer producers the flexibility to prioritize planting winter cereals first, soon after fall corn harvest; and to choose which fields should be LATE BM or LATE IM based on fall crop establishment, costs, and nutrient management regulations. Provided winter annuals are well established and risk of plant damage is low, combining LATE manure application with injection can potentially increase ryelage recovery of more manure–N in ryelage and leave more manure–N in the soil for the subsequent corn crop or potential leaching loss.

CONCLUSIONS

As hypothesized, this study found multiple management options to potentially reduce manure-N losses by different pathways and allow for some flexibility in the selection of farm management strategies. Ryelage offers an additional feedstock and can significantly reduce residual soil N, which if returned with cover crop biomass or left in the soil, might contribute to greater nutrient pollution. In this study, ryelage produced more biomass and took up more manure–N than cover crops. Without supplemental N, corn silage yields were reduced after ryelage but total harvested forage was greater after ryelage than cover crops.

Alternatively, in most treatments soil NO₃⁻–N (%ManureN-S) was greater after cover crops than ryelage. This likely supplied more N for the subsequent corn, as corn silage yields were greater after cover crops than ryelage. Although cover crops have the potential to conserve more N in the soil for the subsequent crop, soil NO₃⁻–N is also vulnerable to leaching loss, particularly during the time between cover crop termination and subsequent crop planting.

Regardless of time of manure application, injecting manure consistently conserved more ManureN-R. Compared to BM, IM decreased NH₄⁻ loss and more N was taken up by ryelage, or contributed to greater soil NO₃⁻–N. Corn silage yields with IM were greater than with BM following cover crops in both years (23%), and following ryelage when manure was applied LATE in both years (21%), and in one of 2 yr when manure was applied EARLY (35%). In both years, total harvested forage was also 20% greater in IM than BM across all treatments. Delaying manure applications resulted in greater soil NO₃⁻–N in LATE IM than EARLY IM. Following cover crops, more soil NO₃⁻–N was available with LATE IM to the subsequent corn crop and yields were greater than EARLY IM. Following ryelage, corn silage yields did not differ with time of application, but manure–N in ryelage was greater with LATE IM than EARLY IM.

ACKNOWLEDGMENTS

The authors thank Tyler Rice, the NESARE Dairy Cropping Systems Research team, technical research support staff, undergraduate students, and the Penn State Russell E Larson Agricultural Research Center Agronomy Farm Staff for assistance with this research. This work was supported by the USDA National Institute of Food and Agriculture, Northeast Sustainable Agriculture Research and Education under Project LNE16-354, and USDA National Institute of Food and Agriculture and Hatch Appropriations under Project #PEN04600 and Accession no. 1009362.

REFERENCES


