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Winter annual management to increase nutrient recovery and forage production on dairies

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Abstract

Management of manure and cereal rye (*Secale cereale* L.) has implications for crop production and nutrient cycling. This 1-yr, full-factorial experiment conducted in Pennsylvania quantified the effects of three management factors—(a) rye management (RyeM; early-terminated cover crop [CC] vs. double crop harvested a week later [DC]), (b) manure application method (ManM; unincorporated broadcast manure [BM] vs. shallow disk injected manure [IM]), and (c) fall field operation prioritization (priority; manure priority [MP] manure application in late September with rye planting in mid-October vs. rye priority [RP], rye planting in late September with manure application in early November)—on rye biomass, nutrient recovery, and forage yield and the effect of ManM and priority on DC forage nutritive value in a rye–corn (*Zea mays* L.) cropping sequence. This experiment was intended to be a repeated 2-yr study, but due to MP treatment rye crop failure in the second year, the resulting 1-yr dataset was analyzed to assess priority effects. Prioritizing rye planting in the fall with DC increased total forage production and apparent N recovery (ANR) when manure was broadcast. These results highlight the value of prioritizing fall rye planting in DC systems to increase rye spring biomass and nutrient recovery when manure is broadcast. More experiments should be conducted on fall field operation timing to develop reliable recommendations.

1 | INTRODUCTION

On dairies with limited manure storage, farmers need to empty manure storage multiple times a year. Fall application of dairy manure is often necessary, but due to a lack of crop nutrient uptake compared with the spring and summer months, this can increase the risk of nutrient pollution to the environment. There are a number of strategies that farmers can implement to minimize this risk.

The use of cover crops (CCs) has been shown to decrease N losses to the environment (Adeli et al., 2011; Staver & Brinsfield, 1998; Teixeira et al., 2016; Tonitto et al., 2006) without decreasing yields of the subsequent crop (Singer et al., 2008; Snapp & Surapur, 2018; Tonitto et al., 2006). Harvesting a double crop (DC) cereal rye (*Secale cereale* L.) may decrease nutrient loss to a greater extent than CC because of increased N uptake associated with longer spring growth (Binder et al., 2020; Milliron et al., 2019). Also, soil nitrate (Ketterings et al.,

Abbreviations: a.e., acid equivalent; ANR, apparent nitrogen recovery; APR, apparent phosphorus recovery; BM, broadcast manure; CC, cover crop; CP, crude protein; DC, double crop; GDD, growing degree day; IM, injected manure; ManM, manure management; MP, manure priority; NDF, neutral detergent fiber; NEL, net energy of lactation; RP, rye priority; RyeM, rye management.

2015; Krueger et al., 2012) and soil test P levels (Brown, 2006) of fertilized fields can be kept in check with nutrient removal through DC harvest (Milliron et al., 2019).

Low-disturbance manure injection is a technology developed for no-till systems as a way to incorporate manure without tillage. Although specialized equipment is required to inject manure (IM) and application is slower than broadcasting manure (BM) (Johnson et al., 2011), IM decreases NH_3 volatilization (Duncan et al., 2017; Powell et al., 2011) and runoff dissolved reactive P, total P, and algal-available P loads (Daverede et al., 2004).

Timing of winter annual planting and manure application can have implications for manure nutrient losses and winter annual nutrient uptake. Early fall planting of winter grass CCs increased CC biomass and nutrient uptake in a North Carolina study (Komatsuzaki & Wagger, 2015). Early-planted fall triticale (×*Triticosecale* Witt.) with fertilizer at planting had greater biomass and N recovery than later-planted triticale (Lyons et al., 2017), and late planting of a CC resulted in insufficient fall growth to decrease soil nitrate levels, highlighting the risk of delaying CC planting (Mays et al., 2003). Delaying manure application to later in the fall when soil and air temperatures are cooler may decrease nutrient losses through slower manure N mineralization (Benbi & Richter, 2002; Dessureault-Rompré et al., 2010) and less ammoniacal N volatilization when manure is surface applied (Akbari et al., 2020; Meisinger & Jokela, 2000). There may be a higher risk of damaging plants when manure is injected (Milliron et al., 2019). However, although chisel shank manure injection into a mixed annual grass CC decreased fall plant density and fall dry matter biomass, spring CC dry matter biomass was not different between CC with and without manure (Singer et al., 2008).

Although studies have explored the effects of these management choices individually, few have looked at their combined effects on manure nutrient recovery and forage production. The objective of this study was to quantify the combined effects of rye management, manure application, and manure application/winter–annual planting sequences. We hypothesized that prioritizing rye planting early in the fall would increase rye biomass and nutrient recovery.

2 | MATERIALS AND METHODS

2.1 | Site description and experimental design

The experiment was conducted at the Russell E. Larson Agricultural Research Center at Rock Springs (The Pennsylvania State University, Pennsylvania Furnace, PA; 40˚42′ N, 77˚58′ W) from September 2016 to October 2017 on a Hagerstown silt loam (fine, mixed, semiactive, mesic Typic Hapludalfs) with portions of 0–3% slope. The field was in oats (*Avena sativa* L.) prior to the experiment. Soil was sampled to a depth of 15.2 cm before rye planting. The soil had pH 6.4, 32 mg kg^{-1} Mehlich-3 extractable P, and 66 mg kg^{-1} exchangeable K. Potash was applied at a rate of 112 kg K_2O ha^{-1} as recommended by the soil test report.

> **Core Ideas**
>
> - Harvesting a rye double crop in addition to corn silage increased forage production by 35–51%.
> - Prioritizing double crop rye planting in fall resulted in 20% more total forage on average.
> - Subsequent corn silage yields were greater with injected manure compared with broadcasted manure.

Experimental plots were 4.6 m by 9.1 m, and all field management was completed via no-till methods. The experiment was repeated in 2017, but rye planted on 18 Oct. 2017 in the MP treatment failed to establish. Therefore, we are reporting the results for 2016–2017.

The two-level, full factorial experiment with three factors (RyeM, ManM, and priority) was arranged in a randomized complete block design with five replicates. Control rye plots for all combinations of RyeM and priority were not applied with manure to calculate ANR and apparent P recovery (APR). Manure N recovery of the aboveground portion was calculated using the formula (Guillard et al., 1995):

$$\text{ANR (\%)} = \frac{\text{Rye aboveground N with manure} - \text{Rye aboveground N without manure}}{\text{Manure total N applied}} \times 100 \quad (1)$$

We calculated APR of the aboveground portion by exchanging P for N in the above formula (Reddy et al., 1999).

2.2 | Agronomic management

A timeline of agronomic management is displayed in Figure 1. ‘Aroostook’ rye (Ernst Conservation Seeds) was seeded at 135 kg ha^{-1} with a Great Plains 1005 solid-stand no-till drill (Great Plains Manufacturing) with rows spaced at 19 cm on 26 Sept. 2016 for the RP treatment and 18 Oct. 2016 for the MP treatment.

Liquid dairy slurry from a large, local dairy was applied at a target wet weight 75,000 L ha^{-1} on all dates for all treatments in line with rye rows. This rate was selected based on USDA survey data of Pennsylvania dairies with high stocking rates (Holly et al., 2019) and was greater than the 45,000 or 52,500 L ha^{-1} used in a previous, similar study (Milliron

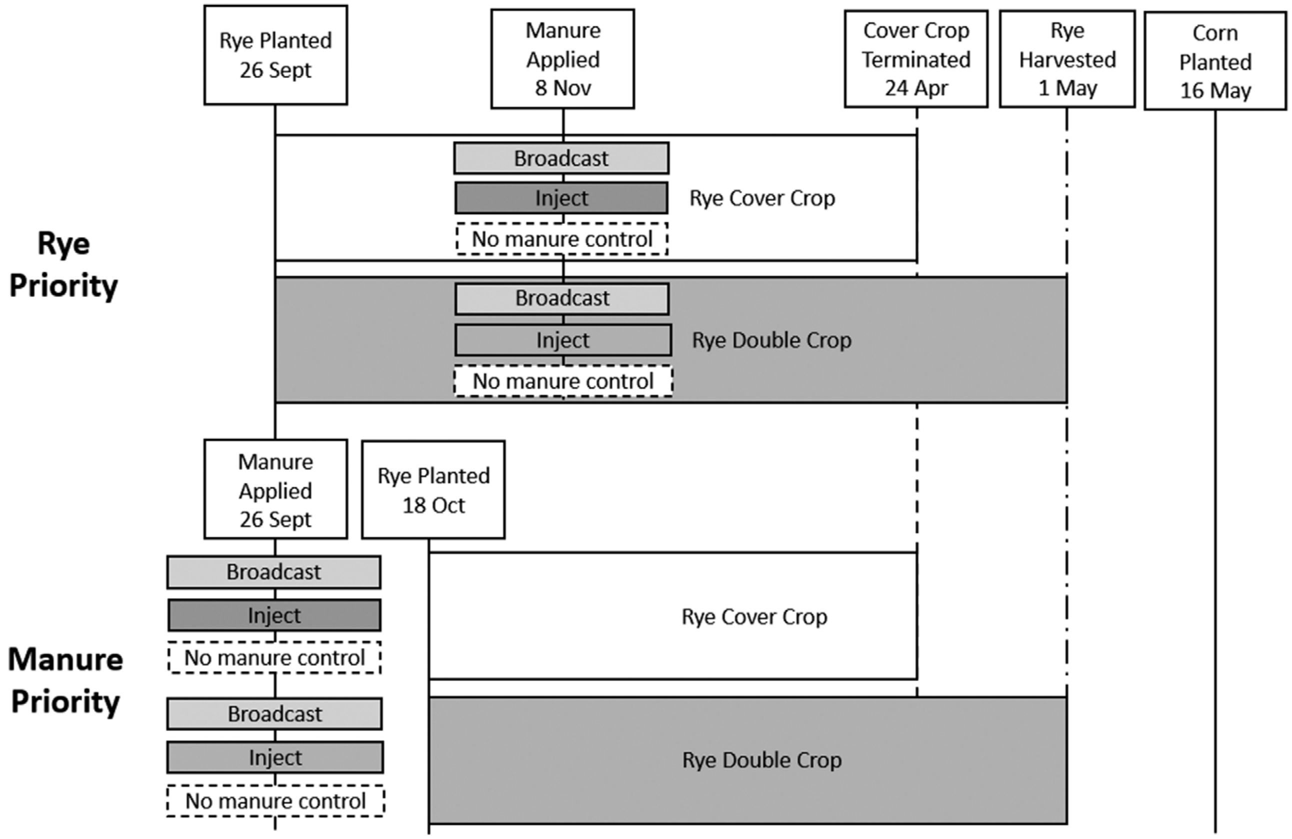

FIGURE 1 Timeline of fall and spring manure and rye management

et al., 2019). Manure was sampled from the spreader at both application dates. Nitrogen concentration was determined by combustion (Watson et al., 2003), and P concentration was determined by microwave-assisted nitric acid digestion and inductively coupled plasma mass spectrometry (Wolf et al., 2003). Application rates were measured with a load cell-equipped manure spreader. Manure was applied on bare ground for the MP treatments on 26 Sept. 2016 at nutrient rates of 106 kg ha^{-1} NH_4–N, 110 kg ha^{-1} organic N, and 38 kg P ha^{-1}. Manure applied at this time had a solids concentration of 10.0%. Manure was applied on established rye in the RP treatments on 8 Nov. 2016 at nutrient rates of 99 kg ha^{-1} NH_4–N, 117 kg organic N ha^{-1}, and 47 kg P ha^{-1}. Manure applied at this time had a solids concentration of 8.3%. Depending on the treatment, BM manure was broadcast with six splash plates or IM manure was injected with six shallow-disc injectors (Yetter Manufacturing) attached to a modified toolbar behind the manure spreader. Shallow-disc injectors were spaced at 75 cm. A drop hose trailing a disk placed manure approximately 10–15 cm below the soil surface and two parabolic disks closed the injection slit. During manure injection, no effort was made to avoid rye plants or inject between rye rows. Other than fall applied manure and 15 kg N ha^{-1} as starter fertilizer (10–20–20) at corn planting, no additional sidedress fertilizer was applied in order to evaluate experimental treatment effects on rye and corn yields and nutrient recovery from manure.

Rye CC treatments were terminated at Feekes Growth Stage 8 on 24 Apr. 2017 (Large, 1954) with 1.26 kg acid equivalent (a.e.) ha^{-1} of glyphosate [*N*-(phosphonomethyl)glycine]. Biomass of CC was measured by hand clipping aboveground plant matter at the soil surface from two 0.25-m^2 quadrats (avoiding the center of the plot where corn yield strips would be harvested) and drying in a 45 ˚C forced-air oven until a constant weight was measured. A yield strip was collected for rye DC with a load-cell equipped 1-m-wide Carter flail harvester (Carter Manufacturing Company) 7.6 cm above ground level at Feekes Growth Stage 10.5 on 1 May 2017, and the rest of the crop was removed with the same machine after sampling for yield. Rye regrowth and weeds were controlled with an application of glyphosate and 2,4-dichlorophenoxyacetic acid (1.26 kg a.e. ha^{-1} glyphosate, 0.53 kg a.e. ha^{-1} 2,4-D) a week after DC harvest. Biomass was sampled from different heights depending on rye treatment to represent farmer practices and to calculate the aboveground rye nutrient pools that were recovered and remained on the soil surface in the case of CC or were removed as silage in the case of DC. Rye DC samples from the yield strip were dried using the same protocol used for the CC to calculate biomass dry matter. Aboveground whole-plant tissue samples from 10 randomly selected plants outside of the center of the plot for CC and DC were collected and N concentration was determined with an Elementar Vario Max N/C analyzer (Horneck & Miller, 1998). Rye P concentration was determined with a nitric acid and peroxide digest (Huang & Schulte, 1985) before analysis by inductively coupled plasma atomic emission spectroscopy (Varian 730-ES, Agilent Technologies).

Corn hybrid TA 583-22D (TA Seeds 108-d relative maturity) was planted on all treatments on 16 May 2017 with a John Deere 1780 no-till planter (Deere & Company) on 76-cm row spacing at 79,040 seeds ha^{-1}. Corn is typically planted 1–2 wk after rye CC termination, but planting is often delayed due to excessive soil moisture or cold weather. Corn was planted for both treatments 15 d after DC harvest. Corn plant population was determined by counting the number of plants in a representative 3-m section per plot approximately 7 wk after planting. A yield strip for corn silage was from two center rows on 29 Sept. 2017 with a front-mounted Champion 1200 chopper (Maschinenfabrik KEMPER). A representative 200-g silage sample was collected at the time of chopping with an integrated Hege sampler (Wintersteiger) and was dried according to the rye protocol to determine moisture content and calculate dry matter yield.

To assess the impact of treatments on rye silage forage quality, we simulated rye silage production by taking 200 g rye DC subsamples from the harvested yield strip, drying them to 60% moisture, and vacuum-sealing them in storage bags to be incubated at 30 ˚C for at least 3 wk (Tanjore et al., 2012) before forage analysis. Near-infrared reflectance spectroscopy (NIRS) was completed with Foss NIRSystems Models XDS and 6500 with ISIScan version 4.6.1. Forage samples were analyzed for crude protein (CP) (AOAC International, 2000), neutral detergent fiber (NDF) (AOAC International, 2000), and net energy of lactation (NEL) (National Research Council, 1989). Total forage dry matter for DC treatment combinations was the sum of DC biomass and subsequent corn silage yield, whereas total forage for CC treatment combinations was simply corn silage yield. Fall and spring growing degree days (GDDs), base 4.4 ˚C (Mirsky et al., 2011), were calculated for rye.

2.3 | Partial budget analysis for DC rye production

We conducted a partial budget analysis to determine if potential increases in IM rye biomass compared with BM rye biomass could compensate for increased cost of IM. Fixed and variable prices were based on prices in the 2016–2017 Penn State Agronomy Guide (Harper, 2016). A survey of manure haulers in Pennsylvania by a Penn State extension agent found that the IM cost US$25 ha^{-1} more than BM (R. Meinen, personal communication, 2016). Average rye silage price came

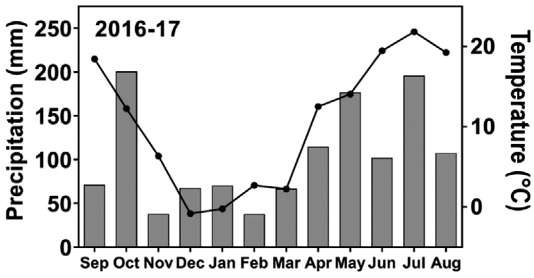

FIGURE 2 Monthly mean temperature (line) and precipitation (bars) from the NRCS Provisional Climatic Data weather station in Rock Springs, PA

from a Pennsylvania average feed price list that is gathered each month and was communicated to us by a Penn State Extension Dairy Specialist (V. Ishler, personal communication, 2019).

2.4 | Statistical analyses

Data were analyzed with PROC MIXED in SAS 9.4 (SAS Institute). For analysis of rye biomass, ANR, APR, corn silage yield, and total forage yield, ManM, RyeM, priority, and their interactions (ManM × RyeM, ManM × priority, RyeM × priority, and ManM × RyeM × priority) were considered fixed effects, and block was considered a random effect. The Satterthwaite approximation for degrees of freedom was used. To test our preplanned hypothesis about the main effects of ManM, RyeM, and priority, we used the 'SLICE' test of PROC MIXED, which is an analysis of simple effects to partition the LSMEANS of interactions (ManM × RyeM × priority) for rye biomass, ANR, APR, corn silage yield, and total forage yield analysis, and differences were considered significant when $p \leq .05$. For analyses of rye silage nutritive values (CP, NDF, and NEL) we compared the fixed effects of ManM and priority. Block was considered a random effect, and differences were considered significant when $p \leq .05$.

3 | RESULTS

3.1 | Weather

Weather data were obtained from the NRCS Provisional Climatic Data weather station at Rock Springs, PA (Figure 2). Average temperature for the week after MP manure application was 13.8 ˚C with no precipitation, whereas average temperature for the week after RP manure application was 5.8 ˚C with 7 mm of rainfall the day after manure application. The following spring growing season was characterized by an early, warm spring with April average temperature 31% higher than the 30-yr normal. In the fall, rye CC and DC accumulated

321 and 147 GDDs for RP and MP, respectively. In the spring, rye accumulated 197 and 286 GDDs for CC and DC, respectively.

3.2 | Rye biomass, ANR, and APR

Rye management (RyeM) ($P = .006$), manure vs. rye priority ($P = .0004$), and the rye management (RyeM) × priority interaction ($P = .02$) were significant for rye biomass. Double cropping (DC) increased rye biomass compared with corresponding CC treatment combinations by 104% for manure priority (MP) and by 112% for rye priority (RP) (Table 1). Rye biomass did not differ between RP and MP for broadcast manure with rye cover crop (RP BM CC vs. MP BM CC), but for all other treatment combinations, RP increased rye biomass compared to MP. Rye priority increased rye biomass for cover crop injected manure (CC IM) by 37%, double crop broadcast manure (DC BM) by 61%, and double crop injected manure (DC IM) by 22% compared with MP treatment combinations (Table 1). Although the main effect of manure management (ManM) was not significant, the preplanned hypothesis tested with the 'SLICE' test indicated that injected manure (IM) increased biomass 28% compared with broadcast manure (BM) only within the double crop manure priority (DC MP) treatments (Table 1).

For ANR, RyeM ($P = .008$), ManM ($P = .04$), and the interaction of RyeM × ManM × priority ($P = .049$) were significant. There was no effect of RyeM on ANR of manure priority broadcast manure (MP BM) treatment combinations, but rye DC increased ANR compared with corresponding rye CC treatment combinations by 158% for manure priority injected manure (MP IM), 114% for rye priority broadcast manure (RP BM), and 74% for rye priority injected manure (RP IM) (Table 1). Injected manure (IM) compared with broadcast manure (BM) did not increase ANR for cover crop manure priority (CC MP) but increased ANR for cover crop rye priority (CC RP) by 85%, 134% for DC MP, and 51% for double crop rye priority (DC RP) (Table 1). Rye priority increased ANR by 70% for DC BM compared with manure priority double crop broadcast manure (MP DC BM) (Table 1).

Main effect RyeM was significant for APR ($P = .02$) as DC increased APR by 70% compared with CC across all treatment combinations (Table 1), but the 'SLICE' test of simple effects showed that DC compared with CC increased APR for both priority treatments, but only with IM by 99% on average across the priority treatment combinations. Although the main effect of ManM was not significant, the 'SLICE' test indicated that IM compared with BM increased APR by 56% only for DC (Table 1).

3.3 | Rye DC forage nutritive value and partial budget analysis

Priority did not affect rye forage nutritive value. However, ManM ($P = .01$) had a significant effect on CP with IM increasing CP by 22% compared with BM across both priority treatments (Table 2).

The average net returns of both DC MP treatments were 68% lower than DC RP treatments net returns. Net returns for DC MP IM were 50% greater than DC MP BM, and the net returns of DC RP BM was 116% greater than DC MP BM (Table 3).

3.4 | Corn silage and total forage yield

Corn populations of the CC RP treatment combinations were 32% lower compared with the average of other treatments (44,896 vs. 66,235 plants ha^{-1}).

Main effects of priority ($P = .02$) and ManM ($P = .02$) were significant for corn yields following rye. Rye priority (RP) and IM both increased corn yield by 10% compared with MP and BM, respectively (Table 4). 'SLICE' tests only indicated a significant difference due to ManM in the DC RP comparison. Injecting manure in the DC RP treatment combination increased corn yield compared to BM by 19% (Table 4).

Effects of RyeM ($P < .0001$), priority ($P = .0002$), ManM ($P = .007$), and RyeM × priority interaction ($P = .02$) were significant on total forage (Table 4). Injecting manure (IM) increased total forage by 10% compared with BM (Table 4). Priority had no effect on total forage with CC treatment combinations, but RP DC increased total forage by 20% compared with MP DC (Table 4).

4 | DISCUSSION

4.1 | Rye biomass

Prioritizing rye planting in the fall over manure application increased rye biomass of CC IM treatment combinations by 37%. Prioritizing rye also increased rye biomass of BM DC by 61% and IM DC by 22% compared with MP treatment combinations. Planting rye 3 wk earlier allowed rye growth to begin when daylength was slightly longer than later in fall, and increased rye fall GDDs by 118% compared with delaying planting when manure was applied first. Earlier fall planting has been shown to increase winter annual biomass in multiple experiments. Lyons et al. (2017) reported that planting triticale 10–25 d earlier in the fall resulted in 21% greater biomass compared with a later planting date in multiple locations in New York, and Mirsky et al. (2011) found

TABLE 1 Aboveground spring rye biomass, and rye apparent N and P recovery (ANR and APR, respectively). Significant differences of main effects (field operation priority [Priority], rye management [RyeM], and manure management [ManM]) were determined by the 'SLICE' statement of SAS PROC MIXED to perform a partitioned *F* test of least squares means (LMEANS) of their interaction

Treatment[a]	**Biomass**	**ANR**	**APR**
	Mg dry matter ha^{-1}	——————%——————	
	***F* test significance**		
Main effect			
RyeM	***	***	***
ManM	NS[†]	***	NS
Priority	***	*	NS
RyeM × ManM	NS	NS	NS
RyeM × Priority	*	NS	NS
ManM × Priority	NS	NS	NS
RyeM × ManM × Priority	NS	NS	NS
	Main effect LSMEAN		
RyeM			
Avg. of CC	NA[b]	18.6b	14.6b
Avg. of DC	NA	37.3a	24.6a
ManM			
Avg. of BM	6.0a[c]	20.2b	18.1a
Avg. of IM	6.3a	23.8a	21.1a
Priority			
Avg. of MP	NA	23.8b	20.1a
Avg. of RP	NA	32.1a	19.0a
	Three-way effect LSMEAN		
Three-way effect combination			
CC MP BM	3.5B[d]**a**[e]**A**[f]	12.0A**aA**	14.9A**aA**
CC MP IM	3.3B**aB**	17.8B**aA**	14.4B**aA**
CC RP BM	4.6B**aA**	15.6B**bA**	15.1A**aA**
CC RP IM	4.5B**aA**	28.9B**aA**	13.7B**aA**
DC MP BM	6.1A**bB**	19.7A**bB**	20.0A**bA**
DC MP IM	7.8A**aB**	45.9A**aA**	31.2A**aA**
DC RP BM	9.8A**aA**	33.4A**bA**	22.2A**aA**
DC RP IM	9.5A**aA**	50.3A**aA**	24.9A**aA**
	SLICE test significance		
SLICE tests			
Effect of rye management (RyeM)			
CC MP BM vs. DC MP BM	***[†]	NS	NS
CC MP IM vs. DC MP IM	***	***	**
CC RP BM vs. DC RP BM	***	**	NS
CC RP IM vs. DC RP IM	***	**	*
Effect of manure application method (ManM)			
CC MP BM vs. CC MP IM	NS	NS	NS
CC RP BM vs. CC RP IM	NS	*	NS
DC MP BM vs. DC MP IM	***	***	*
DC RP BM vs. DC RP IM	NS	**	NS

(Continues)

TABLE 1 (Continued)

Treatment[a]	Biomass	ANR	APR
Effect of field operation priority system (Priority)			
CC MP BM vs. CC RP BM	NS	NS	NS
CC MP IM vs. CC RP IM	*	NS	NS
DC MP BM vs. DC RP BM	***	*	NS
DC MP IM vs. DC RP IM	**	NS	NS

[a]CC, cover crop; DC, double crop; BM, broadcast manure; IM, injected manure; MP, manure priority; RP, rye priority.
[b]Average not reported due to significant interaction.
[c]Lowercase letters (a, b) denote differences due to main effects at $p < .05$.
[d]Uppercase letters (A, B) denote RyeM treatments that differ at $p < .05$ within the same ManM and priority via the 'SLICE' procedure.
[e]Bold lowercase letters (**a**, **b**) denote ManM treatments that differ at $p < .05$ within the same RyeM and priority via the 'SLICE' procedure.
[f]Bold uppercase letters (**A**, **B**) denote priority treatments that differ at $p < .05$ within the same RyeM and ManM via the 'SLICE' procedure.
*Significant at the .05 probability level.
**Significant at the .01 probability level.
***Significant at the .001 probability level.
[†]NS, nonsignificant.

that spring rye biomass increased with earlier fall planting by 65% when the earliest and latest planting dates were compared. Prioritizing rye planting may also decrease the probability of crop failure and give farmers more flexibility as MP rye failed to germinate in the second year of our study (Binder et al., 2020).

Harvesting rye as a DC increased rye biomass approximately twofold. A 1-wk delay in rye harvest as DC compared with termination as CC increased rye spring GDDs by 45%. Previous studies have shown that delaying termination of a winter annual in the spring can increase biomass (Komatsuzaki & Wagger, 2015; Krueger et al., 2011; Mirsky et al., 2011).

Manure injection in the RP system visibly damaged rye stands, but there was no significant difference in spring biomass between injection and broadcast treatments. Damage to winter crop may dissuade farmers from applying manure late in the fall, but our study and others show that this is not always the case. In a study with manure injection into a winter rye–oat mixture, injection decreased plant density by 25%, but spring biomass was not affected (Singer et al., 2008).

In the DC MP treatment, IM increased rye biomass by 28% compared with BM. This is similar to results reported by Milliron et al. (2019) in an experiment on the same farm, and with the same injection equipment in which manure injection increased DC rye biomass for early-applied but not late-applied manure. Early in the fall, IM likely conserved N by decreasing manure NH_3 volatilization, thereby increasing N in the soil for rye to utilize. However, there was less benefit of injection with late manure application, likely due to already low volatile N losses from broadcast application in cool weather.

4.2 | Rye ANR

Although ANR trended larger with all RP combinations compared with MP combinations, the only significant difference was a 70% increase for the DC–BM combination. Applying manure to established rye 6 wk after planting compared with applying manure 3 wk before planting may have decreased N runoff losses (Kleinman et al., 2005) and increased rye nutrient uptake (Aronsson et al., 2016; Beckwith et al., 2010). Cooler temperatures the week after manure application may have slowed N mineralization (Dessureault-Rompré et al., 2010) and may have decreased manure NH_3 volatilization (Beauchamp et al., 1982), thus possibly decreasing N losses and conserving N for rye utilization in spring. In an experiment with warmer temperatures than those in our experiment, tall fescue (*Festuca arundinacea* Schreb.) with surface-applied dairy manure in the summer had a smaller ANR compared with fescue with a manure application in the spring, when temperatures were cooler (Bittman et al., 1999).

Managing rye as a DC vs. as a CC increased ANR by 74 – 158%. Other studies have also demonstrated increases in rye N recovery by delaying spring termination or harvest (Hashemi et al., 2013; Komatsuzaki & Wagger, 2015; Milliron et al., 2019; Mirsky et al., 2017).

Apparent N recovery (ANR) was ~90% greater with IM compared with BM for three out of four comparisons. In other studies, manure injection increased grassland crop total N ANR compared to BM by 27–63% (Mattila et al., 2003), 47% (Schils & Kok, 2003), and in spring barley (*Hordeum vulgare* L.) (Mattila, 2006).

TABLE 2 Rye forage nutritive value analysis including crude protein (CP), neutral detergent fiber (NDF), and net energy of lactation (NEL). Significant differences of main effects (field operation priority [Priority] and manure management [ManM]) were assessed by the 'SLICE' statement of SAS PROC MIXED to conduct a partitioned *F* test of least squares means (LSMEANS) of their interaction

Treatment[a]	CP	NDF	NEL
	——%——		MJ kg^{-1}
	***F* test significance**		
Main effect			
Factor			
ManM	*	NS[†]	NS
Priority	NS	NS	NS
ManM × Priority	NS	NS	NS
	Main effect LSMEAN		
ManM			
Avg. of BM	12.7b[b]	68.6a	1.88a
Avg. of IM	15.5a	66.3a	2.00a
Priority			
Avg. of MP	14.0a	66.8a	2.00a
Avg. of RP	14.1a	68.0a	1.88a
	Three-way effect LSMEAN		
Three-way effect combination			
DC MP BM	12.9**b**[c]**A**[d]	67.0**aA**	1.96**aA**
DC MP IM	15.1**aA**	66.7**aA**	2.00**aA**
DC RP BM	12.5**bA**	70.2**aA**	1.79**aA**
DC RP IM	15.8**aA**	65.9**aA**	1.96**aA**
	SLICE test significance		
SLICE tests			
Effect of manure application method			
DC MP BM vs. DC MP IM	*	NS	NS
DC RP BM vs. DC RP IM	*	NS	NS
Effect of priority			
DC MP BM vs. DC RP BM	NS	NS	NS
DC MP IM vs. DC RP IM	NS	NS	NS

[a]BM, broadcast manure; IM, injected manure; MP, manure priority; RP, rye priority; DC, double crop.
[b]Lowercase letters (a, b) denote differences due to main effects at $p < .05$.
[c]Bold lowercase letters (**a**, **b**) denote ManM treatments that differ at $p < .05$ within the same RyeM and priority according to the 'SLICE' procedure.
[d]Bold uppercase letters (**A**, **B**) denote priority treatments that differ at $p < .05$ within the same ManM and RyeM according to the 'SLICE' procedure.
*Significant at the .05 probability level.
[†]NS, nonsignificant.

TABLE 3 Partial budget of rye double crop planted later in the fall in a manure priority (MP) system or planted early in the fall in a rye priority (RP) system with either broadcast (BM) or injected (IM) manure

Treatment	MP BM	MP IM	RP BM	RP IM
Avg. rye silage yield, Mg dry matter ha^{-1}	6.1	7.8	9.8	9.5
Gross income, US$				
Price, US$ Mg^{-1}	202.90	202.90	202.90	202.90
Sale revenue, US$ ha^{-1}	1,237.70	1,582.60	1,988.40	1,927.60
Input costs				
Manure application, US$ ha^{-1}	39.20	63.90	39.20	63.90
Other fixed costs and variable costs, US$ ha^{-1}	552.90	552.90	552.90	552.90
Total input costs, US$ ha^{-1}	592.10	616.80	592.10	616.80
Net profit, US$ ha^{-1}	645.60	965.80	1,396.30	1,310.80

4.3 | Rye APR

Harvesting rye as DC increased rye APR by 99% compared with CC for both priority treatments, but only when manure was injected. Within the DC MP comparison, injecting manure increased rye APR when compared with broadcasting. Injecting manure into the soil may have reduced P runoff losses (Daverede et al., 2004; Maguire et al., 2011), enabling rye to take up a greater proportion of manure P. Also, the P in the surface-applied BM may have been physically unavailable to the rye. In another CC study with IM, a rye–oat mixture with biomass 1.3 Mg ha^{-1} did not have greater P uptake than a no-manure control with 1.1 Mg ha^{-1} biomass (Kovar et al., 2011), suggesting that a CC may need to accumulate a certain amount of biomass before differences in P uptake or recovery are observed. Our 2-yr study showed a 126% increase in rye APR when rye was double-cropped, regardless of manure application method (Binder et al., 2020). Many studies have shown that winter annuals terminated later in the spring recover more manure (Milliron et al., 2019) and fertilizer N (Komatsuzaki & Wagger, 2015; Mirsky et al., 2017), but there is a lack of studies on the temporal effects of winter annual manure P recovery. This 1-yr study demonstrates that a 1-wk delay in rye spring harvest can increase APR.

4.4 | Rye DC nutritive value

As IM increased rye ANR compared with BM, rye CP also increased by 22%. This increase is similar to a previous study in which injected pig slurry increased winter wheat (*Triticum aestivum* L.) protein concentration compared with surface slurry application, probably because a decrease in NH_3 volatilization increased the amount of plant-available N in the soil (Nyord et al., 2012).

TABLE 4 Corn silage yield and total forage. Significant differences of main effects (rye management [RyeM], field operation priority [Priority], and manure management [ManM]) were determined by 'SLICE' statement of SAS PROC MIXED to conduct a partitioned *F* test of least squares means (LMEANS) of their interaction

Treatment[a]	2017 Corn yield	2017 Total forage
	——Mg dry matter ha^{-1}——	
RyeM		
Avg. of CC	17.4a[b]	NA[c]
Avg. of DC	16.6a	NA
ManM		
Avg. of BM	16.2b	20.2b
Avg. of IM	17.8a	22.2a
Priority		
Avg. of MP	16.2b	NA
Avg. of RP	17.8a	NA
Factor		
RyeM	NS[†]	***
ManM	*	*
Priority	*	***
RyeM × ManM	NS	NS
RyeM × Priority	NS	*
ManM × Priority	NS	NS
RyeM × ManM × Priority	NS	NS
CC MP BM	16.3A[d]**a**[e]**A**[f]	16.3B**aA**
CC MP IM	17.2A**aA**	17.2B**aA**
CC RP BM	17.9A**aA**	17.9B**aA**
CC RP IM	18.3A**aA**	18.3B**aA**
DC MP BM	14.4A**aA**	20.5A**bB**
DC MP IM	16.8A**aA**	24.6A**aB**
DC RP BM	16.1A**bA**	25.9A**aA**
DC RP IM	19.1A**aA**	28.6A**aA**
SLICE tests		
Effect of rye management (RyeM)		
CC MP BM vs. DC MP BM	NS	**
CC MP IM vs. DC MP IM	NS	***
CC RP BM vs. DC RP BM	NS	***
CC RP IM vs. DC RP IM	NS	***
Effect of manure application method (ManM)		
CC MP BM vs. CC MP IM	NS	NS
CC RP BM vs. CC RP IM	NS	NS
DC MP BM vs. DC MP IM	NS	**
DC RP BM vs. DC RP IM	*	NS
Effect of field operation priority system (priority)		
CC MP BM vs. CC RP BM	NS	NS
CC MP IM vs. CC RP IM	NS	NS
DC MP BM vs. DC RP BM	NS	***
DC MP IM vs. DC RP IM	NS	**

[a]CC, cover crop; DC, double crop; BM, broadcast manure; IM, injected manure; MP, manure priority; RP, rye priority.
[b]Lowercase letters (a, b) denote differences due to main effects at $p < .05$.
[c]Average not reported due to significant interaction.
[d]Uppercase letters (A, B) denote RyeM treatments that differ at $p < .05$ within the same ManM and priority according to the 'SLICE' procedure.
[e]Bold lowercase letters (**a**, **b**) denote ManM treatments that differ at $p < .05$ within the same RyeM and priority according to the 'SLICE' procedure.
[f]Bold uppercase letters (**A**, **B**) denote priority treatments that differ at $p < .05$ within the same RyeM and ManM according to the 'SLICE' procedure.
*Significant at the .05 probability level.
**Significant at the .01 probability level.
***Significant at the .001 probability level.
[†]NS, nonsignificant.

4.5 | Rye DC partial budget

Manure priority IM increased rye DC yields enough to increase net returns by 50% compared with MP with BM. This is similar to a study by Milliron et al. (2019), who found that an increase in rye DC biomass due to manure injection compared with BM early in the fall offset the increased cost of manure injection. Rye priority combinations averaged 68% greater net returns than MP combinations because of greater rye biomass due to earlier planting, but injecting manure after rye was established did not increase returns on investment.

Although injecting manure early in the fall can increase rye DC yield by enough to offset the greater cost of application, planting rye first and applying manure later resulted in a greater financial benefit when assessing the rye DC production of the farm budget.

4.6 | Subsequent corn yields

In this 1-yr dataset, subsequent corn silage yields increased when rye planting was prioritized in the fall. Prioritizing rye planting in the fall may have allowed more manure N to be conserved and utilized by the rye, which could then be released to the subsequent corn crop after the rye was terminated in the CC system and began to decompose.

With the exception of the RP IM combination comparison, corn silage yields trended lower with DC rye vs. rye CC, possibly due to N removal by rye DC with no additional N fertilization of corn in this experiment. Decreases in corn yields after DC have been reported both in experiments with no additional fertilization in the subsequent crop (Krueger et al., 2011; Milliron et al., 2019) and in experiments with additional spring N fertilization (Heggenstaller et al., 2008; Nafziger et al., 2016), suggesting that decreases in summer annual yields after winter DCs cannot always be attributed to nutrient deficits. To compare differences between CC and DC treatments due to nutrient dynamics and to remove the likely effect of planting date on summer corn yield, corn was planted on the same day for both rye management treatments. Because DC is usually harvested later than a CC would be terminated, a summer annual following a CC may be planted earlier than a summer annual planted after a DC, leading to a yield advantage for the annual after the CC (Darby & Lauer, 2002).

Subsequent corn silage yields were greater with IM than with BM. Injecting manure increased corn silage after RP DC rye by 19% compared with RP DC rye with BM. Rye priority DC rye likely had the greatest opportunity to use manure N, thus making it the most competitive with corn for N compared with other treatment combinations. Injecting manure likely conserved enough N in the soil or in belowground rye biomass for corn use. Double-cropping rye presents an opportunity to increase forage production, but a rye DC can also deplete nutrients that could be used by a following crop. Conserving manure N by injecting manure with a rye DC is one way to decrease N limitations for a subsequent summer annual.

4.7 | Total forage production

Harvesting a rye DC in addition to harvesting a summer crop increased total forage by 35% in the MP treatment and by 51% in the RP treatment. Double crop systems have increased total forage compared with single-crop systems by 25% (Heggenstaller et al., 2008), 20% (Milliron et al., 2019), 29–44% (Binder et al., 2020), and 8.4–15.9% (Brown, 2006).

When rye was harvested as DC, prioritizing rye planting in fall rather than manure application resulted in 20% more total forage on average across both manure management methods. On average, IM increased total forage by 10% compared with BM, and the 'SLICE' test indicated this was primarily due to the increased total forage produced in the DC MP treatment. This is similar to another study at our location that found an increase in total forage due to IM (Milliron et al., 2019). In our 2-yr study, when rye planting was prioritized and harvested as a DC, manure injection also increased total forage production (Binder et al., 2020).

5 | CONCLUSIONS

Our experiment demonstrated the viability of a DC rye–corn rotation for forage in the northeastern United States to increase N and P utilization and potentially reduce the loss of these nutrients to the environment. Prioritizing rye planting in the fall over manure application increased rye biomass in CC IM and both DC comparisons, thus also increasing total forage 20%. Although we recommend these practices be evaluated over more years and locations across this region, our experiment highlights numerous benefits of prioritizing rye planting in the fall over manure application including increases in rye biomass, rye N recovery, and forage production when harvested as forage. Injecting manure into an established rye stand did not affect spring rye biomass but increased subsequent corn yields after the RP DC.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

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