Sustainable intensification of corn silage cropping systems with winter rye

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Abstract

Winter rye (*Secale cereale* L.) is a popular cover crop in North Central United States for preventing soil erosion and nutrient losses, among other agronomic and ecosystem benefits. Winter rye can also be a high-quality spring forage option when double-cropped with corn silage (*Zea mays* L.), thus adding diversity to monocrop rotations. However, these sustainability-promoting benefits have potential trade-offs including soil nutrient immobilization and decreased corn yields. We hypothesized that winter rye would promote sustainable intensification of corn silage, as substantiated by decreased nitrogen budget and soil nitrate without yield loss. We also predicted that winter rye double-cropped and harvested as a forage would maintain total production (corn silage + rye harvest) compared to corn silage alone. This five-season study is representative of continuous corn silage systems in North Central United States, and Wisconsin specifically, distinguished by fall liquid dairy manure applications. Corn was planted after rye termination or harvest, and varying rates of nitrogen were applied to corn. As predicted, rye cover reduced preplant soil nitrate without affecting corn silage yield. Rye harvested as a forage crop reduced preplant and in-season soil nitrate, and total production equaled or exceeded corn silage yields without rye, despite a 13% decrease in corn silage yield. The 5-year nitrogen balance demonstrated almost 40% reduction in excess nitrogen in the rye forage system. This novel study demonstrated no cumulative or single-year agronomic limitations to winter rye implementation in manured, corn silage systems characteristic of North Central United States over a range of seasonal weather conditions. Furthermore, the dual use of rye as a cover crop conservation practice or harvested as a forage double-crop makes it agronomically advantageous and demonstrate potential for sustainable intensification in this system. This research is the first to show that sustainable intensification through double cropping dairy-based systems can increase high-quality biomass production while reducing nitrogen losses to the environment.

Keywords Cover crop · Winter rye · Forage · Nitrogen · Corn silage · Double-cropping · Manure

Abbreviations

RyeCC Rye cover crop
RyeHarv Rye harvested as forage
NoCC No cover crop

1 Introduction

Continuous corn (*Zea mays* L.) silage is a common crop production system in the dairy-centric North Central United States corn belt region, covering 320,000 ha (10%) of Wisconsin's principal crop production area in 2016 (USDA NASS 2017). Corn silage is high-quality feed for cows, and the early fall harvest allows for a liquid dairy manure application prior to soil surface freezing. However, when harvesting corn for silage, most aboveground biomass is removed from the field, leaving the soil surface largely exposed for the majority of the year (Fig. 1, “No cover”), which results in nutrient losses over the winter and early spring months (Jokela and Casler 2011). Nutrients and soil lost from corn silage systems in North Central United States contribute to eutrophic nutrient loading of freshwater in the Mississippi River Basin and ultimately hypoxia in the Gulf of Mexico (Kladivko et al. 2014).

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Fig. 1 Soil coverage over the course of a year in various corn silage cropping systems with vs without winter rye, North Central United States. The pie charts depict proportions of a year attributable to crop coverage and field operations. Without a fall-seeded winter rye cover crop (“No cover”), there is little residue left after corn silage harvest (a), leaving the soil surface bare and exposed (“Winter, spring fallow” slice) for all but the 4-month corn silage growing season. This also results in soil

surface exposure during the corn growing season (b). A winter rye cover crop (“Rye cover”) increases soil coverage over the year, both when actively growing in the spring (c) and following spring termination (d). Extending the winter rye growing season and harvesting rye as a forage (“Rye harvested as forage”; e) delivers high-quality forage, minimizes spring fallow, and provides soil coverage extending into the corn growing season (f)

Further, high-removal continuous corn silage systems result in net soil carbon loss (Cates and Jackson 2018). Given these environmental and economic drawbacks, growers need viable strategies to retain nutrients on farm in order to maintain long-term productivity and profitability, and continue to intensify production spatially and temporally to satisfy growing demand (Cassman 1999). Cover crop implementation is generally recognized as an accessible in-field method of reducing nutrient export from fields by 40–70% compared to winter bare fallow (Tonitto et al. 2006). Fall-seeded winter rye (*Secale cereale* L.) establishes well in the short and cool fall growing period characteristic of North Central United States, providing soil coverage during otherwise fallow months and maintaining a growing crop nearly year-round (Fig. 1, “Rye cover”). Reported benefits include improved soil-water holding properties (Basche et al. 2016), increased carbon inputs as residue, root, and microbial biomass (Faé et al. 2009), improved soil biology (Rankoth et al. 2019), improved infiltration to curb runoff and soil erosion (Ranaivoson et al. 2017), and immobilization of nutrients that might otherwise be susceptible to leaching (Blanco-Canqui et al. 2015).

Despite ecosystem and management benefits of winter rye cover crop use, adoption rates are relatively low due to lagging structural support and ambiguous economic benefits for the grower (Ketterings et al. 2015; Roesch-McNally et al. 2017). Further, there is a perceived risk that cover crops reduce yield of the subsequent cash crop, though meta-analyses by Marcillo and Miguez (2017) and Tonitto et al. (2006) found mean corn yield response to be unaffected by grass cover

crops, with variability dependent upon tillage, location, and fertilization. Cover crop research frequently demonstrates annual variations in yield and other responses that necessitate caveat-peppered conclusions and recommendations (Duiker and Curran 2005; Martinez-Feria et al. 2016), not dissimilar from agronomic research in general. Economic and agronomic drawbacks associated with winter rye cover cropping may be offset when rye biomass is harvested as a spring forage double-crop, thus incentivizing adoption through tangible returns (Plastina et al. 2018) while maximizing soil coverage over the year (Fig. 1, “Rye harvested as forage”). Overall, research has demonstrated that harvesting winter rye as a forage crop can make up for ensuing corn silage yield loss or surpass corn silage production alone (Faé et al. 2009; Fouli et al. 2012; Marcillo and Miguez 2017), though some studies have demonstrated decreases in total production when double-cropping (e.g., Krueger et al. 2012). Decreased corn silage yield in double-crop systems is most often attributed to nutrient immobilization associated with decomposition of the cover or delayed corn planting due to forage harvest timing (Thelen and Leep 2002). Regarding purported water stress following a forage double-crop, Fouli et al. (2012) found no effect of cover cropping on soil water content over two discrete growing seasons, Martinez-Feria et al. (2016) found slight differences in soil water content only in dry years, and Basche et al. (2016) found increased soil water using rye cover crop during drought conditions. Under excessively wet spring conditions, a rye cover crop can arguably improve planting conditions by enhancing evapotranspiration of excessive soil

moisture. Further, rye forage harvest allows for control over residue removal, whereas termination of a cover crop leaves all biomass on the soil surface, potentially preventing soil drying and warming (Blanco-Canqui et al. 2015) and contributing to nutrient immobilization.

The question remains if this type of agricultural intensification satisfies the overarching goals of sustainable intensification, described by Cassman (1999) as the increase in net production to meet global demand while maintaining environmental quality. Numerous studies suggest that this corn silage-winter rye double-crop system can mitigate environmental concerns associated with intensive corn silage production (Thelen and Leep 2002; Faé et al. 2009; Krueger et al. 2012; Ketterings et al. 2015). Use of winter rye in North Central United States is a well-demonstrated practice that may help satisfy numerous long-term management goals at the nexus of soil health and water quality that are highly relevant under our changing climate and the associated increase in extreme weather events (IPCC 2013) and concomitant water runoff and soil erosion events (Fouli et al. 2012). Additionally, there are aspects of cover cropping that may participate in climate change mitigation and adaptation, such as reduced soil carbon and nitrogen emissions, and increased soil surface albedo (Blanco-Canqui et al. 2015; Basche et al. 2016; Kaye and Quemada 2017). There is also a growing body of work quantifying cover crop-affected aspects of soil biology as they relate to soil carbon storage and soil health (Poeplau and Don 2015; Austin et al. 2017; Rankoth et al. 2019).

Studies that continue to substantiate potential for short- and long-term agronomic and environmental sustainability are needed to increase cover crop adoption and effective, risk-mitigated management (Ketterings et al. 2015). This study is novel in that it spans five seasons and thus covers a wider breadth of weather patterns, including a drought in 2012. The literature is also lacking in consistent yield and forage quality, which may suggest imprecise management. Further, due to a robust dairy industry and cooler climate, Wisconsin has the most area in corn silage production of any North Central state by almost double in any given year (USDA NASS 2017), but the literature lacks Wisconsin-specific studies under this intensive cropping system. Our objective was to assess and quantify the agronomic and environmental benefits and trade-offs associated with incorporation of winter rye as a cover crop and winter rye harvested as a forage double-crop in continuous corn silage. Specifically, we measured yield and quality of corn silage and winter rye forage, changes in soil nitrate-nitrogen ($\text{NO}_3\text{-N}$), and calculated the nitrogen (N) balance after 5 years of corn silage with and without winter rye at various rates of in-season N application. We hypothesized that winter rye use could contribute to sustainable intensification of continuous corn silage cropping systems. In order to satisfy this hypothesis, we tested predictions that winter rye would reduce soil $\text{NO}_3\text{-N}$ concentrations prior to corn planting and

that winter rye harvested as a forage would compensate for any decrease in corn silage yield, i.e., combined rye forage and corn silage yield would meet or exceed the yield of corn silage alone. Further, we predicted that a simple N balance (inputs minus removal) would demonstrate a reduction in excess environmental N following 5 years of a tightly coupled corn silage and winter rye forage double-crop rotation.

2 Materials and methods

2.1 Experimental site, experimental design, and cultural practices

A five-season field experiment was conducted from 2011 to 2016 at the University of Wisconsin Arlington Agricultural Research Station (43°18'16"N, 89°22'59"W, 307 m asl) in Arlington, WI, USA, on a Plano silt loam soil (fine-silty, mixed, superactive, mesic Typic Argiudoll). Corn silage was grown annually with varying rates of applied N following a fall liquid dairy manure application and cover crop treatments. Manure was applied after corn silage harvest each year between September 15 and October 10 at rates ranging from 90,700 to 115,000 L ha^{-1} . Total manure-N content, estimated available N, and manure application methods are detailed for each year in Table 1.

The experimental design was a randomized complete block split-plot design with three replicates. Treatments occurred in the same plots for the duration of the 5-year study. For statistical purposes, the first whole plot factor was study year, and the second whole plot factor was cover crop, including winter rye as a cover crop (RyeCC), winter rye harvested as a forage crop (RyeHarv), and no cover crop (NoCC) treatments. The split-plot factor was N rate; either 67, 112, or 179 kg N ha^{-1} in the form of ammonium nitrate was broadcast applied at sidedress (approximately V3 growth stage). These N rates were chosen to represent underapplication, recommended application, and overapplication rates based on the recommended rate of 184 kg N ha^{-1} for corn silage on high-yield potential soils in WI (Laboski et al. 2006) minus the 72 kg N ha^{-1} estimated available N content of the manure applied in fall of 2011 (Table 1). Our objective with the various N rates was to test the effect of winter rye as a cover crop or as a forage with regard to the recommended N rate for corn. The N rates were held consistent over the course of the study and not adjusted based on the actual annual manure-N application and estimated availability. Starter fertilizer was applied at corn planting to all plots at a rate providing 6 kg N ha^{-1} , 16 kg P_2O_5 ha^{-1} , and 47 kg K_2O ha^{-1} .

Winter rye (Spooner variety) was drill seeded between September 23 and October 19 each year following manure application at approximately 110 kg ha^{-1} pure live seed. In the RyeCC treatment, winter rye was terminated with a

Table 1 Fall-applied manure details and nitrogen (N) balance in corn silage with no cover crop, winter rye cover crop, and winter rye harvested as a forage crop

Crop year Manure parameter	Cover treatment:			No cover crop			Rye cover crop			Rye harvested as forage		
	$kg\ N\ ha^{-1}$	N rate:	$kg\ N\ ha^{-1}$	67	112	179	67	112	179	67	112	179
2012	Total manure-N	239	N applied	312	357	424	312	357	424	312	357	424
	Application		N removed	179	142	168	151	160	169	244	243	245
	Est. available N	72	N balance	133 (6.3)	215 (19.8)	256 (8.4)	161 (1.4)	197 (6.2)	255 (11.5)	68 (5.8)	114 (8.6)	179 (15.5)
2013	Total manure-N	297	N applied	369	414	481	369	414	481	369	414	481
	Application		N removed	188	218	212	195	202	214	218	257	256
	Est. available N	119	N balance	181 (8.2)	196 (11.4)	269 (22.0)	174 (21.8)	212 (18.4)	267 (12.6)	151 (8.4)	157 (13.3)	225 (6.2)
2014	Total manure-N	260	N applied	304	349	416	304	349	416	304	349	416
	Application		N removed	305	262	313	277	310	292	294	297	309
	Est. available N	104	N balance	-1 (4.4)	87 (39.9)	103 (13.7)	27 (31.5)	39 (28.7)	124 (24.3)	10 (12.8)	52 (22.8)	107 (9.1)
2015	Total manure-N	290	N applied	362	407	474	362	407	474	362	407	474
	Application		N removed	277	288	300	301	299	310	305	349	354
	Est. available N	87	N balance	85 (23.4)	119 (7.3)	174 (34.0)	61 (6.5)	108 (19.2)	164 (20.8)	57 (19.0)	58 (18.0)	120 (6.2)
2016	Total manure-N	166	N applied	234	279	346	234	279	346	234	279	346
	Application		N removed	237	241	260	187	244	216	288	310	351
	Est. available N	66	N balance	-3 (19.2)	38 (31.7)	86 (7.5)	47 (18.8)	35 (25.3)	130 (23.5)	-54 (2.4)	-31 (2.8)	-5 (14.0)
5-year cumulative N balance				395 (22.0)	655 (51.5)	888 (57.3)	470 (37.0)	591 (30.4)	940 (62.5)	232 (14.0)	350 (29.4)	626 (2.9)

N applied includes total N content of liquid dairy manure ("Total manure-N") applied in the fall prior to crop year, in-season N rate application (67, 112, or 179 kg N ha⁻¹), and 6 kg N ha⁻¹ in starter fertilizer. N removed includes corn silage N content and winter rye forage N content in that treatment. N balance is the N applied less the N removed (with *standard error*) and is meant to serve as a relative indicator of potential system loss characteristic of each treatment combination. Estimated available N from manure is 30% total N of unincorporated manure and 40% total N of manure injected or incorporated within 72 h of application (Laboski et al. 2006)

standard burndown rate of glyphosate between April 11 and May 9; the NoCC treatment was sprayed concurrently. In the RyeHarv treatment, the winter rye growth period was extended beyond the termination date for RyeCC. For optimum forage quality and yield, rye was chopped and harvested at the “boot stage” (Feeke’s scale 10.0; Thelen and Leep 2002) and stubble sprayed between May 10 and May 31. In this system, the rye forage biomass would typically be harvested and ensiled. There was no tillage to incorporate the rye cover or rye forage residue. Cover crop plots measured 43 m $\times$ 9 m (12 corn rows), and N rate split-plots measured 43 m $\times$ 3 m (4 corn rows). Corn was planted at 0.76 m row spacing in all treatments following rye forage harvest in 2012 and 2013 and split planted in RyeCC and NoCC versus RyeHarv (i.e., delayed corn planting in RyeHarv treatment) in 2014, 2015, and 2016.

The crop preceding the study was corn silage in 2011. Prior to the beginning of the study, a composite soil sample collected across the entire study area to a depth of 15 cm indicated 7.0 pH, 3.1% organic matter, 31 mg P kg⁻¹, and 98 mg K kg⁻¹. At the conclusion of the study, composite soil samples per cover crop whole plot to a depth of 15 cm indicated field means of 7.2 pH, 3.0% organic matter, 29 mg P kg⁻¹, and 131 mg K kg⁻¹, with no statistically significant differences by cover crop treatment.

2.2 Sample collection and analysis

Mean monthly air temperature (mean of daily maximum and minimum temperatures) and total monthly precipitation are presented as deviations from the 30-year normal (1980 through 2010) as reported for the research farm by NOAA. Winter rye aboveground biomass was sampled from two random areas (0.74 m² total) within each RyeCC and RyeHarv whole plot just prior to rye termination or rye harvest, respectively, and dried at 60 °C. Corn silage yield was determined by hand harvest of 3 m of row from each of two center rows per split-plot at approximately 65% moisture. Biomass was weighed, mechanically chopped, subsampled, and dried at 60 °C to determine moisture content at the time of harvest. Corn silage, rye harvested as forage, and total forage yields are reported on a dry matter basis. All dry biomass samples were mechanically ground to pass through a 0.5 mm sieve, and total N concentrations of rye biomass from RyeCC plots, rye forage from RyeHarv plots, and corn silage from each split-plot were determined by flash combustion using a Flash EA 1112 CHN Automatic Elemental Analyzer (Thermo Finnigan, Milan, Italy).

Nitrogen balance was calculated by first quantifying cumulative N inputs over the course of five seasons to each cover crop $\times$ N rate split-plot (total N in fall manure + N in starter fertilizer + N applied to corn in-season) less the N content of harvested plant material (corn silage + rye harvested as forage,

where applicable). For clarification, N content of the rye cover biomass in RyeCC treatment was not included in this calculation because this biomass was not removed from the field.

Composite samples of corn silage representing each year $\times$ cover crop $\times$ N rate treatment were analyzed for the following forage quality parameters: crude protein, acid detergent fiber, neutral detergent fiber, total digestible nutrients, net energy for lactation, and estimated milk production equivalent. Rye forage from each RyeHarv whole plot was also subsampled and analyzed for the same forage quality parameters.

To assess the effect of cover crop treatment on soil NO₃-N, soil samples were collected from each cover crop whole plot at the time of rye termination or rye harvest and in-season just prior to the corn sidedress N application. Each sample was a composite of six cores (1.8 cm diameter) collected to a depth 0–60 cm (separated 0–30 and 30–60 cm at preplant) or 0–30 cm (in-season). Soil NO₃-N was measured following extraction with 2 M KCl using the vanadium reduction of NO₃ method as described in Doane and Horwath (2003). Because all soil samples were collected prior to the in-season N application each year, there is no separation of N rate treatments in the soil NO₃-N data. The substantial rate of fall-applied manure would obscure a clear interpretation of the effect of in-season N application rate on residual soil NO₃-N.

2.3 Statistical analysis

Corn silage yield and total forage yield (corn silage plus winter rye forage production in RyeHarv treatment) were subjected to an ANOVA based on experimental design using the MIXED model procedure for SAS (version 9.2, SAS Institute, Cary, NC). Year, cover crop, N rate, and interactions between these treatment factors were treated as fixed effects. Block and its interaction with the whole-plot factors (year and cover crop treatment) were treated as random effects. Year was a repeated measure using heterogeneous Toeplitz (TOEPH) and heterogeneous first-order autoregressive [ARH(1)] covariance structure models for corn silage yield and total forage production, respectively, chosen for best fit determined by lowest Akaike’s information criterion. Due to a significant year $\times$ cover crop treatment interaction effect, data were also analyzed separately by year. Soil NO₃-N data were analyzed using a similar approach as yield data, without the N rate fixed effect because soil samples were composited across cover crop whole plots. Corn silage quality data were subjected to an ANOVA using the MIXED model procedure for SAS with cover crop, N rate, and interactions between these treatment factors treated as fixed effects and year and its interaction with cover crop and N rate treatments treated as random effects. The cumulative N balance data were subjected to an ANOVA using the MIXED model procedure for SAS with cover crop, N rate, and interactions between these treatment factors treated as fixed effects and block and its interaction

with cover crop treatment treated as random effects. All treatment means were estimated using method of residual maximum likelihood (Searle et al. 2009); statistical significance was determined at $\alpha = 0.05$. The LSMEANS statement was used for post hoc comparison of means corresponding to significant treatment effects.

3 Results and discussion

3.1 Weather

Mean monthly air temperatures for the winter rye growing period (September through April) and corn growing season (May through September) were generally above normal (compared to 30-year averages reported by NOAA for Arlington, WI, 1980 through 2010) for the double-crop seasons 2011–2012 and 2015–2016, whereas temperatures trended below normal for seasons 2012–2013 and 2013–2014. Monthly precipitation totals were 43% below normal during the 2012 drought with only 29 cm of precipitation falling May through September. June 2014 had 24 cm precipitation (compared to 12 cm normal), which helped to compensate for otherwise droughty conditions that year. Precipitation from September 2015 through September 2016 was 27 cm above normal. This variability in weather conditions over a 5-year study is ideal, because we are better able to discern the potential behavior of this cropping system over time under changing climatic conditions.

3.2 Winter rye growth

Winter rye aboveground biomass production in the RyeCC treatment averaged 3.44, 0.34, 0.36, 0.28, and 3.08 Mg dry matter ha^{-1} in 2012, 2013, 2014, 2015, and 2016, respectively (standard error (SE) = 0.11, 0.04, 0.03, 0.03, 0.08). Mean N content of winter rye aboveground biomass was 129, 12, 12, 10, and 83 kg ha^{-1} (SE = 6.1, 1.7, 1.1, 1.3, 9.4). Winter rye forage yield in the RyeHarv treatment averaged 5.5, 2.3, 3.0, 3.3, and 6.0 Mg dry matter ha^{-1} (SE = 0.19, 0.06, 0.23, 0.14, 0.22) with mean N removal of 135, 67, 73, 93, and 105 kg ha^{-1} in 2012 through 2016, respectively (SE = 8.2, 6.3, 5.1, 8.7, 4.6). The range of these values and the increase in biomass from the time of cover crop termination to the time of forage harvest is in line with previous findings in North Central United States (Krueger et al. 2012; Basche et al. 2016). The tenfold increase in RyeCC aboveground biomass and N uptake in 2012 and 2016 as compared to other years and the twofold increase in rye forage yield in the RyeHarv treatment in the same study years may be attributed to temperatures exceeding normal in the associated rye growth periods (mean monthly temperature 2.25 and 3.25 °C above normal September through April for 2011–2012 and 2015–

2016, respectively), particularly in contrast to below normal temperatures during rye growth periods in the other study years (also observed in Martinez-Feria et al. 2016). With climatic shifts in Wisconsin toward higher mean annual temperatures punctuated by earlier onset of spring and later onset of winter (Wisconsin Initiative on Climate Change Impacts 2011), winter cover crops are poised for higher production potential in future seasons, and thus increased ecosystem services such as prevention of soil erosion by both wind and water (Blanco-Canqui et al. 2015) and reduction in soil nitrate concentrations (Martinez-Feria et al. 2016). The high rye biomass values in RyeCC in 2012 and 2016 and in RyeHarv in all years would be sufficient for a 50% reduction in water runoff and 80% reduction in soil erosion according to a meta-analysis done by Ranaivoson et al. (2017). Although belowground biomass was not quantified, previous work suggests that belowground production may match aboveground production of winter rye biomass in this context (Austin et al. 2017; Cates and Jackson 2018).

3.3 Soil nitrate

Averaged over the 5 study years, mean preplant soil $\text{NO}_3\text{-N}$ concentrations for NoCC, RyeCC, and RyeHarv, respectively, were 14.4, 8.3, and 5.3 mg N kg^{-1} at 0–30 cm and 14.3, 11.5, and 4.6 mg N kg^{-1} at 30–60 cm; repeated measure analysis demonstrated a main effect of cover crop treatment (Table 2). Annual variation reflected weather trends to some extent in that increased rainfall from September 2012–April 2013 and September 2015–April 2016 may have contributed to low soil $\text{NO}_3\text{-N}$ measured at preplant in 2013 and 2016 at both depths (Fig. 2), whereas low rainfall in September 2014–April 2015 agrees with higher preplant soil $\text{NO}_3\text{-N}$ in 2015 at both depths. Repeated measure analysis also demonstrated a year $\times$ cover crop treatment interaction effect on preplant soil $\text{NO}_3\text{-N}$ (Table 2). Accordingly, soil $\text{NO}_3\text{-N}$ data were also analyzed separately for each study year. There was a main effect of cover crop on preplant soil $\text{NO}_3\text{-N}$ at 0–30 cm in 4 out of 5 years (2012, 2013, 2014, and 2016; $p < 0.05$), indicating RyeCC and RyeHarv treatments significantly reduced soil $\text{NO}_3\text{-N}$ at 0–30 cm as compared to NoCC and the RyeHarv treatment further reduced soil $\text{NO}_3\text{-N}$ compared to RyeCC in 2013 and 2014 (Fig. 2). The reduction in soil $\text{NO}_3\text{-N}$ carried through at 30–60 cm in 2012 ($p = 0.0011$; RyeCC and RyeHarv $<$ NoCC) and 2014 ($p = 0.0149$; RyeHarv $<$ NoCC and RyeCC; Fig. 2). These results support our prediction that the rye treatments would significantly reduce soil $\text{NO}_3\text{-N}$ at preplant, thus indicating lower concentrations of environmentally reactive and mobile N in the soil profile at this critical time when significant spring leaching events occur prior to corn planting or crop demand for N (Blanco-Canqui et al. 2015).

Table 2 Mean dry matter corn silage yield and total forage yield (corn silage + rye harvested as forage in rye harvest treatment only) with ANOVA results as affected by year (repeated measure), cover crop treatment, and N rate treatment

	Corn silage yield	Total forage yield	Preplant NO ₃ -N 0–30 cm	Preplant NO ₃ -N 30–60 cm	Sidedress NO ₃ -N 0–30 cm
Year	----- Mg dry matter ha ⁻¹ -----		----- mg N kg ⁻¹ -----		
2012	12.7 d	14.6 c	11.6 ab	10.7 ab	9.7
2013	20.4 b	21.2 b	5.3 c	7.7 bc	9.6
2014	23.2 a	24.1 a	10.8 b	12.9 a	10.0
2015	23.3 a	24.4 a	14.6 a	14.5 a	13.1
2016	18.6 c	20.6 b	4.4 c	4.9 c	9.1
Cover Crop					
No cover crop	20.5 a	20.5 b	14.4 a	14.3 a	14.0 a
Rye cover crop	20.7 a	20.7 b	8.3 b	11.5 ab	11.2 b
Rye harvested as forage	17.8 b	21.8 a	5.3 c	4.6 b	5.7 c
N rate, kg ha ⁻¹					
67	19.1 b	20.5 b			
112	19.6 ab	21.0 ab			
179	20.2 a	21.6 a			
Source of variation	<i>p</i> value				
Year	< 0.0001	< 0.0001	< 0.0001	0.0331	0.1356
Cover crop	< 0.0001	0.0042	< 0.0001	0.0408	< 0.0001
Year × cover	0.0004	0.0475	0.0041	0.0072	0.0211
N rate	0.0165	0.0089			
Year × N rate	0.4135	0.4447			
Cover × N rate	0.2849	0.2336			
Year × cover × N rate	0.2383	0.2681			

Preplant soil nitrate-N (NO₃-N) and in-season “sidedress” soil NO₃-N measured in cover crop whole plots prior to annual in-season N application, with ANOVA results as affected by year (repeated measure) and cover crop treatment. Within each column for significant treatment factors, means followed by the same letter are not significantly different ($\alpha = 0.05$)

Fig. 2 Preplant soil nitrate-N (NO₃-N) varied by study year and cover crop treatment. Within each study year and sampling depth, bars annotated with different letters are significantly different ($\alpha = 0.05$).

Cover crop treatments are: NoCC = no cover crop; RyeCC = rye cover crop; RyeHarv = rye harvested as forage. Error bars represent standard error

Mean in-season soil $\text{NO}_3\text{-N}$ collected just prior to sidedress, 0–30 cm, was 14.0, 11.2, and 5.7 mg kg^{-1} ($\text{SE} = 1.2, 0.5, 0.4$) across study years in NoCC, RyeCC, and RyeHarv, respectively, and repeated measure analysis showed main effect of cover crop and year $\times$ cover crop treatment interaction effect (Table 2). Analysis within each year demonstrated a main effect of cover crop on in-season soil $\text{NO}_3\text{-N}$ at 0–30 cm at sidedress ($p < 0.05$, all years); RyeHarv had significantly lower soil $\text{NO}_3\text{-N}$ than that of NoCC and RyeCC (all years; in-season data not graphed).

The reduction in $\text{NO}_3\text{-N}$ in RyeHarv measured at preplant and extending into the corn growing season compared to RyeCC is expected given that the rye in the RyeHarv treatment grew for a longer period of time, producing more measured aboveground biomass and presumably more root biomass (Austin et al. 2017), with an increased likelihood of net N immobilization upon decomposition (Martinez-Feria et al. 2016). After the decrease in soil $\text{NO}_3\text{-N}$ concentrations observed at preplant in RyeCC relative to NoCC, the in-season “rebound” of soil $\text{NO}_3\text{-N}$ in RyeCC to concentrations similar to those observed in NoCC implies timely release of N from the rye cover biomass. This is desirable and indicates that nutrient release timing may meet crop need, and immobilization is less likely to decrease corn yield.

The lack of a cumulative trend in soil $\text{NO}_3\text{-N}$ as the study years progressed and weak responses of rye forage yield and corn silage yield attributable to N rate (section 3.4, Table 2) indicate that excess N was either lost from the system, as estimated by the N balance approach (Section 3.6, below), or maintained to some extent in decomposing biomass, potentially contributing to soil carbon accumulation (Poeplau and Don 2015).

3.4 Yield

Repeated measure analysis demonstrated main effects of year, cover crop, and N rate on corn silage yield and on total forage yield (Table 2). As predicted, there was no statistically significant difference between corn silage yield in NoCC or RyeCC, and total forage yield in the RyeHarv treatment was significantly greater than NoCC or RyeCC, despite corn silage yielding 13% and 14% lower in RyeHarv compared to NoCC and RyeCC, respectively. On average, mean total forage production over 5 years was 6–7% higher in the RyeHarv treatment than corn silage alone in NoCC (Table 2), which is an encouraging result for a moderate adjustment to an already highly productive cropping system. This suggests one potential avenue toward intensification focused on increased production without exacerbating environmental issues such as soil and water quality, as advocated by Cassman (1999). Annual differences seen in mean yields reflect the main weather patterns observed: Drought in 2012 combined with a slight increase in mean monthly temperatures resulted in the lowest yields of

any year. Decreased corn silage yields also were associated with excess rainfall and increased temperatures in 2016, though only a moderate decrease in total forage yield (Table 2). The highest yielding years were 2014 and 2015, which were the most typical study years regarding temperature and precipitation. Repeated measure analysis also demonstrated an advantage in corn silage and total forage yields at the overapplication rate of 179 kg N ha^{-1} rate compared to the underapplication rate of 67 kg N ha^{-1} , though no clear differences in yields between the recommended rate of 112 kg N ha^{-1} and either the over or underapplication rates (Table 2).

The repeated measure analysis also demonstrated a year $\times$ cover crop treatment interaction effect (Table 2); therefore, the following analysis of yield data by study year was completed to tease out annual responses. Notably, corn silage yields in RyeCC and NoCC treatments were statistically similar in each study year. The significant effect of cover crop treatment on corn silage yield in 2012 and 2014 (Table 3) was driven by a 15% decrease in corn silage yield in RyeHarv treatment compared to RyeCC and NoCC treatments in 2014 and 34% decrease in 2012 under drought conditions. Corn planting was delayed in the RyeHarv treatment in 2014, 2015, and 2016, which may have contributed to decreased corn yield in that treatment in 2014, though unapparent in 2015 or 2016. Reductions in corn silage yield in the RyeHarv treatment are offset by yield of rye biomass harvested as forage, as is demonstrated by the statistically similar total forage yields in study years 2012 through 2015 (i.e., lack of significant effect of cover crop treatment), and significant increase in total forage yield in RyeHarv in 2016 by 23% and 26% as compared to corn silage production in NoCC and RyeCC treatments, respectively.

Though repeated measure analysis reflected increased yield with 179 kg N ha^{-1} compared to 67 kg N ha^{-1} , analysis within each year demonstrated that N rate only had a significant effect on yields in 2013, for both corn silage and total forage yields (Table 3). This may be explained by the generally lower soil $\text{NO}_3\text{-N}$ concentrations at preplant in 2013 (Fig. 2), possibly due to N immobilization resulting from the combination of high rye biomass production and drought conditions in 2012 that may have impeded rye decomposition. Alternatively, soil $\text{NO}_3\text{-N}$ may have decreased due to excess rainfall from September 2012–April 2013. The applied N apparently made up for any potential deficit in soil $\text{NO}_3\text{-N}$ with regard to yield, similar to other studies demonstrating potential for increased N rate to offset potential N immobilization and resultant crop yield loss (Martinez-Feria et al. 2016; Ranaivoson et al. 2017).

The neutral effect on corn silage yield in RyeCC is an expected (Practical Farmers of Iowa and Iowa Learning Farms 2019) yet still encouraging response as others have periodically found rye cover to result in corn silage yield declines, particularly under high levels of rye biomass growth

Table 3 Mean annual dry matter corn silage yield and total forage yield (corn silage + rye forage in rye harvest treatment only) with ANOVA results as affected by cover crop treatment and N rate treatment

	Corn silage yield					Total forage yield				
	2012	2013	2014	2015	2016	2012	2013	2014	2015	2016
Cover Crop	-----Mg dry matter ha ⁻¹ -----									
No cover crop	14.1 a	20.7	23.9 a	24.1	19.4	14.1	20.7	23.9	24.1	19.4 b
Rye cover crop	14.6 a	20.7	24.8 a	24.8	18.5	14.6	20.7	24.8	24.8	18.5 b
Rye harvested as forage	9.4 b	19.9	20.7 b	21.1	17.9	15.0	22.1	23.7	24.4	23.9 a
N rate, kg ha ⁻¹										
67	12.5	19.3 b	22.9	22.8	18.0	14.4	20.1 b	23.9	23.9	20.0
112	12.4	20.9 ab	24.8	23.5	18.4	14.2	21.7 a	23.8	24.6	20.4
179	13.3	21.0 a	23.8	23.7	19.4	15.1	21.8 a	24.8	24.8	21.4
Source of variation	<i>p</i> value									
Cover crop	0.0002	0.3894	0.0021	0.0539	0.4986	0.4541	0.1346	0.5267	0.7722	0.0100
N rate	0.1076	0.0025	0.5713	0.4466	0.5034	0.1076	0.0025	0.5789	0.4466	0.5034
Cover crop × N rate	0.1145	0.5042	0.6507	0.1648	0.4621	0.1145	0.5042	0.6608	0.1648	0.4621

Within each column for significant treatment factors, means followed by the same letter are not significantly different ($\alpha = 0.05$)

(Krueger et al. 2012; Marcillo and Miguez 2017). The greater total forage yield in the RyeHarv system (Table 2), without the requirement more N in most years (Table 3), demonstrates that sustainable intensification is possible when connected with dairy production (manure input and forage output) in North Central United States. There was no apparent cumulative treatment effect on yield as the study progressed over five seasons, given that the low yields in the first study year (2012) were attributed to severe drought.

3.5 Forage quality analysis

Analysis of corn silage quality parameters across all years indicated a statistically significant effect of N rate on the crude protein content of corn silage ($p = 0.0147$). Mean crude protein at 67 kg N ha⁻¹ was 7.97%, which was a significant reduction from 8.43% at 179 kg N ha⁻¹. The other quality parameters evaluated indicated no significant effect of cover crop or N rate treatments or treatment factor interaction. The following are mean values for corn silage quality parameters over the course of the study (and SE): 8.22% crude protein (0.12), 24.1% acid detergent fiber (0.36), 43.8% neutral detergent fiber (0.52), 65.1% total digestible nutrients (0.22), 1.47 Mcals kg⁻¹ net energy for lactation (0.01), and 1543 kg Mg⁻¹ milk production (9.04).

Analysis of rye forage quality was completed to ensure that the rye forage was a high-quality feed option. The following are mean values for the quality parameters over the course of the study (and SE): 17.6% crude protein (0.94), 29.3% acid detergent fiber (1.0), 49.0% neutral detergent fiber (1.8),

70.6% total digestible nutrients (0.91), 1.59 Mcals kg⁻¹ net energy for lactation (0.026), and 1759 kg Mg⁻¹ milk production (43.8). Compared to corn silage, the rye forage had higher crude protein content and higher associated milk production estimates. However, the acid detergent fiber, which is a largely undigestible fraction (Hoffman and Shaver 2004), was also typically greater in rye forage.

Though somewhat distinct feeds with unique nutrient characteristics, the rye harvested as forage generally measures up to corn silage as a high-quality forage option, and as such the yields were not adjusted for nutrient content. Thus, total forage yield is a simple sum of dry matter yields of corn silage and rye harvested as forage. Though beyond the scope of this paper, a full nutrient and economic analysis of this production system could assess nuanced trade-offs in forage quality and overall dietary structure. Further, there may be some cultural limitations to overcome as rye forage is mainly considered a feed option for pre-lactational heifers. Our results, however, provide evidence that intensifying a corn silage production system in this way over multiple years has the potential to increase total biomass with higher crude protein content and associated milk production estimates and thus may help to encourage adoption as this system can increasingly be seen as a net benefit to dairy operations.

3.6 Nitrogen balance

The N balance presented here is meant to serve as a means of treatment comparison and relative indicator of potential system excess based on accounting of known inputs and outputs

and does not represent N loss measured through edge-of-field monitoring, which is inherently problematic because the mechanisms of N loss are nonpoint source (e.g., nitrate leaching, soil erosion by wind or water, N_2O emissions; Kladvko et al. 2014). Analysis of the cumulative N balance over the 5-year study period indicates a significant effect of both cover crop and N rate treatments ($p < 0.0001$ for both treatment factors; Fig. 3) with no treatment factor interaction ($p = 0.1864$). Cumulative 5-year N balances for NoCC, RyeCC, and RyeHarv were 646, 667, and 403 kg N ha^{-1} , respectively. Cumulative N balance of RyeHarv was about 40% lower than NoCC or RyeCC ($p < 0.0001$), indicating that a large quantity of N was removed in the RyeHarv system that otherwise would have been susceptible to environmental loss without double-cropping. NoCC and RyeCC were statistically similar, though this calculation in no way captures the amount of N taken up by the growing rye cover crop. The fate of rye biomass-N is unknown, but the decreased soil $\text{NO}_3\text{-N}$ concentration at preplant and sidedress in RyeCC relative to NoCC (Table 2) indicates that a portion of N was tied up in the terminated rye biomass, though not to such an extent that corn silage yield indicated cover crop-related N immobilization in RyeCC (Table 2). The aboveground N content of rye biomass in the RyeCC treatment exhibited extremes (129, 12, 12, 10, and 83 kg N ha^{-1} in the respective study years) and represents over 35% percent of the cumulative N balance for RyeCC. This uptake of N, though not removed from the system, potentially slows and buffers leaching loss to the environment (Tonitto et al. 2006; Austin et al. 2017) and might contribute to the accumulation of soil carbon, based on substantial evidence that unharvested cover crops can contribute to the accumulation of soil carbon in a review by Poeplau and Don (2015).

N balances across cover treatments by N rate treatment were 366, 531, and 818 kg N ha^{-1} for 67, 112, and 179 kg N ha^{-1} , respectively ($p < 0.0001$ for all treatment differences). Interestingly, the applied N rate $\times$ 5 (years of application) is nearly equivalent to the respective N balances, which underscores the lack of yield benefit in all but one study year from the added N beyond 67 kg N ha^{-1} (Table 3), and also serves to conceptually convert the excess applied N directly to potential environmental loss. The reduced N balance achieved by double-cropping with winter rye as a forage bolsters potential for sustainable intensification (Cassman 1999). Overall, the cumulative N balances are high and demonstrate excess due to the high application rate of manure, though we only expect 30–40% of manure-N to be available to the crop (Laboski et al. 2006). This is a negative characteristic of manure-based systems, though other research demonstrates that manure has a high carbon content and can contribute to soil organic carbon stabilization (Kirchmann et al. 2004). In this study, we inadvertently applied a range of manure-N rates, which could be attributable to variability of manure characteristics and the inherent challenges of calibrating machinery for

Fig. 3 Cumulative N balance after five growing seasons. Points represent mean cumulative N balance in corn silage systems for cover crop $\times$ N rate treatments after 5 study years (fall 2011 through fall 2016; bars represent standard error). Cumulative N balance was calculated as follows: Total N additions (N in manure, starter fertilizer, and in-season application of ammonium nitrate) minus N content of harvested corn silage and rye forage (in rye harvest treatment only)

plot-scale application. Improvements to manure-N management can play a large role in decreasing N balances and thus potentially reducing N loss from these systems.

This research is novel because we demonstrated consistent levels of agronomic production (Tables 2 and 3) associated with implementation of a winter rye cover crop in manured continuous corn silage over five seasons with a range of weather conditions in WI, where corn silage covers almost twice the area of any other North Central state. Soil coverage was substantially increased over the course of a year (Fig. 1), thus mitigating vulnerability to soil degradation and potentially improving water quality as forecasted by reductions in N balance and soil $\text{NO}_3\text{-N}$ (Figs. 2 and 3). Continued research is needed to inform precise management of tightly coupled rotational systems that are accessible and attainable by growers interested in sustainable intensification. This is how growing market demands can be met in the short term while simultaneously mitigating trade-offs in environmental quality over the long term. Areas of future interest may include comparison of other winter cover/forage crops such as triticale, potential for climate change mitigation with respect to carbon storage in high biomass removal systems, and potential for managed N to enhance soil carbon accumulation in agricultural systems such as these.

4 Conclusion

Winter rye use delivered multifaceted improvements that demonstrate the potential for sustainable intensification of continuous corn silage in North Central United States over the course of five growing seasons. Environmentally, use of fall-seeded winter rye reduced cumulative N balance by about

40% when rye was harvested as a forage double crop, forecasting potential for improved water quality and decreased emissions of the potent greenhouse gas N_2O , as evidenced by decreases in soil nitrate prior to corn planting—when this environmentally reactive and mobile form of N is most vulnerable to loss from the agricultural system to the environment. Further, winter rye aboveground biomass-N alone comprised over 35% of the cumulative N balance in the cover crop treatment, indicating potential mitigation or dampening of N loss compared to the no cover crop treatment. These environmental wins sometimes come with agronomic trade-offs, but the rye cover crop did not affect optimal N need or yield of the subsequent corn silage crop and thus is not expected to affect nutrient management in this study system. Total forage yield was equal to or higher than corn silage alone when rye was managed and harvested as a forage double-crop while increasing in-field diversity and soil coverage over the year and diversifying high-quality feed options for growers. As pressure increases for higher milk production so does pressure on our soils to increase production spatially and temporally. Results from this study demonstrate that: (1) dairy farmers can use cover crops to achieve conservation efforts without risk to total forage production and (2) sustainable improvements to dairy production systems in North Central United States is attainable with winter forage crops. Considering the changing climate characterized by more extreme weather events that may impact soil quality and resilience, it is essential to focus on long-term management goals that improve soil water holding capacity, infiltration, ground coverage, and that otherwise prevent soil erosion. Integration of cover crops is widely recognized as a means of addressing these goals, and employing the option to use cover crops as a forage option speaks to the added goals of sustainable intensification of our most productive croplands.

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Data availability Reasonable requests for the datasets from this study will be honored by the corresponding author.

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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