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RESEARCH ARTICLE

Potential of winter double crops and tillage for managing manure-based nutrient loading

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Abstract

Aims Intensive dairy regions have an opportunity to enhance recycling of manure nutrients within forage rotations improving the system sustainability. This study investigated the combined effect of winter double crops and tillage on nutrient uptake, yield, and forage quality under annual manure applications with silage corn (*Zea mays*).

Methods The 2×4 split block study consisted of conventional (CT) vs minimal (MT) tillage, and combinations of manure (M) vs synthetic fertilizer (S) and winter triticale (x *Triticosecale*) (D) vs fallow (F) for each tillage type. Plant tissue was collected for annual forage yield, nutrient concentrations, and forge quality.

Results In soils, M significantly increased SOC, TN, Olsen P, K, Na, and Zn (20–96%) along with multiple enzyme activities (45–75%) and decreased NH_4-N and Ca (9–26%) compared to synthetic fertilizers, regardless of tillage and winter crop. Manure increased tissue N, P, and K for both corn silage (12–39%) and triticale (31–45%) regardless of tillage. However, tillage effects were seen for corn Na and triticale Mg, Na, Zn, Ca, and Mn. Triticale removal of all nutrients was significantly greater with manure application (77- 97%) regardless of tillage. While inclusion of winter double crop removed 1.1 – 1.8 times as much NPK as winter fallow, triticale tissue K exceeded maximum concentrations for feed forages. Manure increased crude protein for both forages; however, M also increased triticale fiber content and reduced feed energy compared to synthetic fertilizer.

Conclusion Winter triticale can increase forage production and enhance manure nutrient utilization in forage rotations.

Keywords Dairy manure · Nutrient cycling · Forage quality · Double crops · Tillage

Abbreviations

TN	Total nitrogen
N	Nitrogen
P	Phosphorous
PSI	Phosphorus site index

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SOM	Soil organic matter
CP	Crude protein
K	Potassium
Ca	Calcium
Mg	Magnesium
Na	Sodium
CEC	Cation exchange capacity
GDD	Growing degree days
CT	Conventional tillage
MT	Minimal tillage
M	Manure
S	Synthetic fertilizer
D	Winter double crop
F	Winter fallow
SOC	Soil organic carbon
DM	Dry matter
ADF	Acid detergent fiber
aNDF	Neutral detergent fiber
EE	Ether extract fat
NE_L	Net energy for lactation

Introduction

Idaho is one of the top milk-producing states in the U.S, ranking third in 2020 (USDA-ERS 2022). Over the last two decades, Idaho's dairy cow inventory has increased by 73%, consisting of 652,000 head of lactating cattle in 2021 (USDA-NASS 2022) with 75% of the cows located in the southcentral region. These cattle are highly concentrated, with 51% of the cows on farms > 5,000 head and 70% of cows on farms > 2,500 head (ISDA 2022). This concentration of cows has led to increased localized nitrogen [N] and phosphorus [P] loads to soil and generated concern over the environmental impact of dairy production in the region. Farmgate surpluses of nutrients, particularly P, have been previously reported (Hristov et al. 2006; Leytem et al. 2021; Spears et al. 2003). Leytem et al. (2021) estimated that to balance manure P production with regional crop P uptake, manure would need to replace fertilizer on 91% of cropland. However, the land area reported to receive manure is 16% of total regional cropland (USDA-NASS 2017), suggesting that there is high nutrient loading on farmland utilized by dairy producers. Due to a buildup of regional soil P through overapplication of manure, the Idaho State Department of Agriculture has required dairies to develop nutrient management plans to regulate the amount of P being land applied and to utilize a P Site Index [PSI] to evaluate the potential risk of offsite P transport (ISDA 2018). Included within the PSI are credits for the use of cover crops and conservation tillage to stabilize nutrients and minimize potential offsite losses.

In areas that have historically received heavy manure applications, the use of cover cropping (double cropping) has gained popularity as a means of stabilizing nutrients over winter and increasing nutrient mining between growing seasons when biomass is harvested (Brown 2006; Brown et al. 2012; Mitchell and Teel 1977; Muir et al. 2001; Reese et al. 2014; Salmerón et al. 2010). Double cropping can also reduce soil erosion, increase C-sequestration, and increase soil organic carbon [SOC] (Dabney et al. 2001; Hunter et al. 2014; Reicosky and Forcella 1998), therefore improving overall soil health. For southern Idaho producers, choices for cover crops are limited by low moisture conditions and shorter growing seasons, with common choices including triticale (x *Triticosecale*), winter wheat (*Triticum aestivum*), pearl millet (*Pennisetum glaucum*), and winter barley (*Hordeum vulgare*) (Hunter et al. 2014). In the intensive dairy producing regions, where forage demands have increased to match cattle feed needs, winter forages provide the added benefit of a dual-purpose crop (Sheffield et al. 2008).

While dual-purpose forage production can provide many benefits for producers, it is important that the forage quality is satisfactory for cattle consumption. Quality standards for protein and fiber content, digestibility, and overall provided energy from forages is critical when determining feed mixes (Allen 1996; Arispe and Filley 2016; Ball et al. 2001) and can be influenced by environmental factors (such as temperature and soil moisture), plant maturity at harvest, and soil nutrient concentrations (Delevatti et al. 2019; Moore et al. 2020). Maturity at harvest plays an integral role in forage digestibility through the accumulation of fibrous cell wall components, which can ultimately lower overall energy value (Moore et al. 2020; NRC 2001). Increasing soil N, whether from fertilizer or manure additions, has been shown to increase crude protein [CP] (Delevatti et al. 2019; Muir et al. 2001). Additionally, high soil test potassium [K] has been associated with increased risk of various metabolic diseases, primarily grass tetany, due to imbalances with forage K: calcium [Ca] + magnesium

[Mg] and sodium [Na] (Allen 1996; Horst et al. 1997; Ishler et al. 2016; Littledike et al. 1981; Moore et al. 2020; Oetzel 2011).

The use of conservation tillage can also play a large role in soil health and nutrient retention. Minimal tillage has been shown to increase soil nutrient concentrations (SOC, N, P, K, Ca, and Mg) and soil water content and decrease bulk density which can lead to increased crop yield compared to conventional tillage (Adekiya et al. 2009; Agbede 2008; Zhang and Blevins 1996). Reduced or no till practices can also improve soil health by increasing residue retention on the soil surface, reduce soil erosion, and increase water infiltration (Dabney et al. 2001; Logan et al. 1991). However, reduced or no tillage practices can result in enhanced stratification of nutrients through the soil profile, increased compaction, weed presence, and risk of nutrient loss from surface applied amendments, which is a particular concern with manure applications (Dabney et al. 2001; Logan et al. 1991; Pexioto et al. 2020).

Developing sustainable forage systems that utilize manure nutrients is a priority for the concentrated dairy regions of Idaho. Information regarding the effects of tillage and cover/double cropping on nutrient uptake and forage quality are needed to enable producers to manage manure nutrients more sustainably while producing high quality forage. The objective of the present study was to determine the effects of heavy manure application, tillage, and the use of a cover/double crop on yield, nutrient uptake, and forage quality in continuous corn silage.

Materials and methods

Site properties

The field site was located at the United States Department of Agriculture Northwest Irrigation and Soils Research Laboratory in Kimberly, Idaho, USA (42°15′0″ N, 114°30′0″ W). According to Web Soil Survey (NRCS 2022), the predominant soil series were a Portneuf silt loam (coarse-silty, mixed, mesic Durixerollic Calciorthids) and a Rad silt loam (coarse-silty, mixed Durixerollic Camborthids). Average cation exchange capacity [CEC] is recorded as 10.8 meq 100 g^{-1}, an average pH of 7.9–8.0, and an average bulk density of 1.35 g cm^{-3} (Web Soil Survey, NRCS 2022). The region has a mean annual temperature of 9.1 °C and mean annual precipitation of 153 mm. Average daily air temperature, cumulative growing degree days [GDD], precipitation, and irrigation data are reported in Fig. 1.

Site setup and agronomic practices

The study began in the fall of 2015 and ended in the fall of 2021. Plots (12.2 × 12.2 m) were established as a split block design with 4 blocks under a continuous silage corn cropping system. Each block was split into two strips with tillage (disk/chisel plow [CT] or strip/no tillage [MT]) randomly assigned within each block. The treatments investigated consisted of a combination of manure (M) or synthetic fertilizer (S) as a nutrient source, either with triticale as a double crop (D) or winter fallow (F). Within each tillage strip, four treatments were randomly assigned and consisted of (1) winter triticale with manure [MD], (2) winter triticale with synthetic fertilizer only [SD], (3) winter fallow with manure [MF], and (4) winter fallow with synthetic fertilizer only [SF]. Solid dairy manure (scraped from dry lots and stacked for several months) was applied annually in the fall at a target rate of 60 Mg ha^{-1} (dry weight basis) prior to seeding of triticale. The application rate was determined based on regional practices to represent the most common manure management scenario resulting in long term buildup of soil nutrients. Treatments without manure received applications of synthetic fertilizers (urea, MAP, and KCl) each spring prior to corn planting, with rates determined by preplant soil sample nutrient contents and University of Idaho guidelines for corn silage (Brown et al. 2010).

As the intent of the present study was to use the winter triticale crop to stabilize end of season nutrients, there was no fertilizer added to the triticale on the synthetic fertilizer only plots. Corn (*Zea mays*) silage was planted using a 4-row, Monosem NG + planter with 76.2 cm row spacing and 15.2 cm between seed placements. Triticale (x *Triticosecale*) was planted using a John Deere No-Till drill (Model 1560) with 19.1 cm row spacing at a seeding rate of 110 kg ha^{-1}.

Seed varieties and planting, harvesting, and fertilizer/manure application dates are reported in Table S1. Corn was planted each year between May and early June and harvested between mid-September

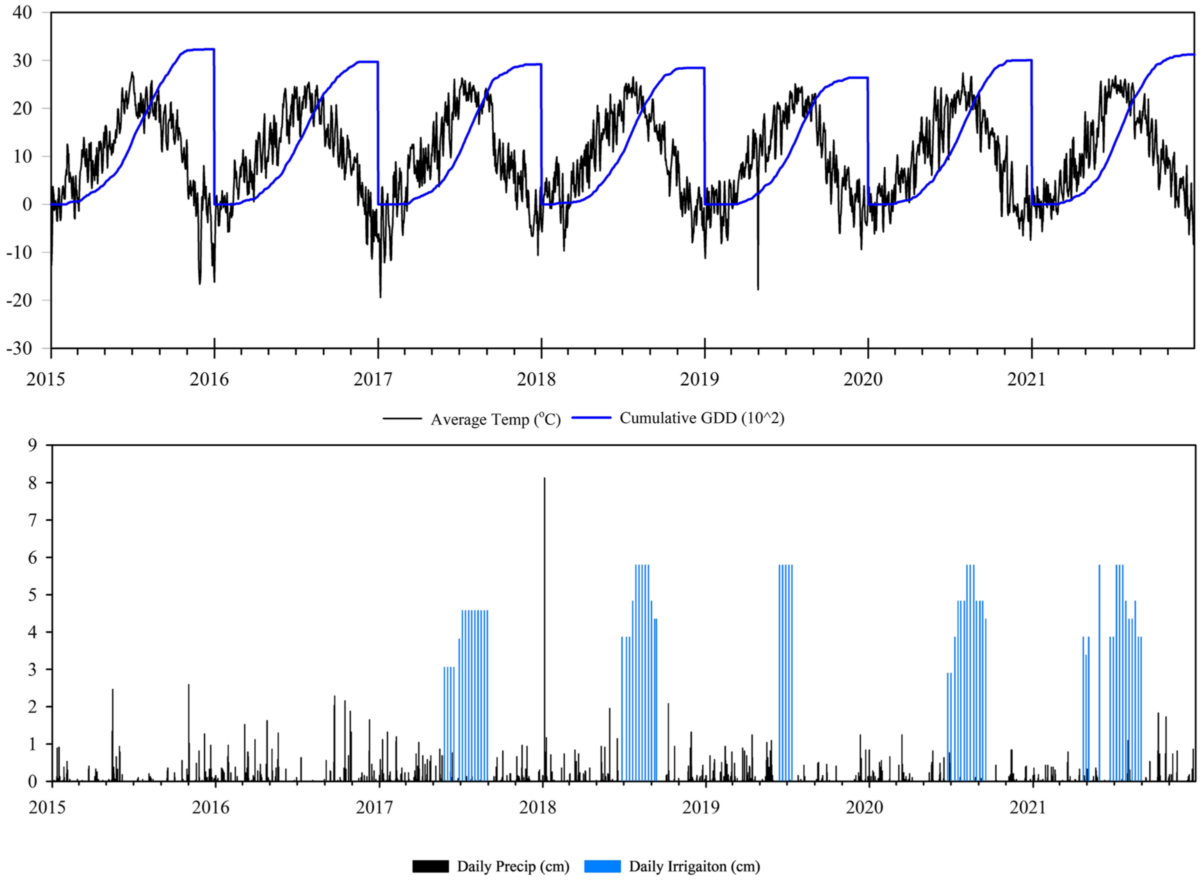

Fig. 1 Average daily air temperature and cumulative growing degree days from 2015 – 2021 (top) and daily precipitation and irrigation events from 2015 – 2021 (bottom). Detailed irrigation information data available starting in 2017

and early October. Herbicides were applied throughout the growing season, with details on source, rate, and application dates being reported in Table S2. In 2015, solid dairy manure was applied in the fall prior to initial corn planting, which occurred in the spring of 2016. For following years, manure was applied 1–2 days prior to triticale seeding in the fall. Triticale was planted between late September and mid-October and harvested between late April and May the following year.

Manure application and analyses

Manure was applied in the fall (September or October) each year by weighing the appropriate amount of manure per plot on a wet weight basis and spreading with a small plot manure spreader. Manure was immediately incorporated in the CT treatments by disking to a depth of 15 cm to minimize ammonia volatilization and P runoff losses over the winter; the fertilizer plots within the tillage strip received the same tillage for consistency. In the MT plots, manure was left on the surface with no incorporation. During application events, manure samples were collected from each plot by placing three trays (0.5 × 0.6 m) within the plots during manure application, composited by plot, and then further composited over plots to obtain four representative samples (one per block). Manure water content was determined gravimetrically on a 100 g subsample by drying at 105 °C for 24 h. Total C and N contents were determined via combustion with a CHN 628 analyzer (LECO, St. Joseph, MN). Total elements (P, K, Ca, Mg, zinc [Zn], Na, and manganese [Mn]) were determined via digestion of 0.5 g manure with nitric/perchloric acid and measurement

Table 1 Select chemical properties of the fall-applied dairy manure, by year. Concentrations are on a dry weight basis

Year	C	N	C:N	P	K	Mg	Ca	Na	Mn	Zn
	g kg^{-1}								mg kg^{-1}	
2015	237.0	16.3	14.5	7.0	28.9	11.6	27.8	12.0	347.2	328.9
2016	245.1	15.2	16.1	6.3	22.0	9.6	25.6	10.7	271.4	150.0
2017	158.3	11.1	14.3	4.5	24.7	13.8	55.7	5.1	407.1	164.5
2018	144.7	10.5	13.8	5.7	24.5	9.3	27.1	6.5	319.7	186.4
2019	176.1	13.4	13.2	7.8	29.7	11.8	28.9	8.5	300.3	164.3
2020	316.4	20.6	15.3	6.5	29.4	12.7	35.4	11.1	289.7	298.1

Table 2 Average application rate of manure and synthetic fertilizer total N, P, and K applied from 2015–2021. For all years, synthetic fertilizers were only applied to fertilizer treatments

	Year	Total N	Total P	Total K	Applied Dry Wt
		kg ha^{-1}			Mg ha^{-1}
Manure					
	2015	1022.4	441.3	1813.7	63.0
	2016	1059.3	438.1	1529.8	69.7
	2017	655.6	265.2	1453.8	59.0
	2018	611.1	331.8	1429.3	58.6
	2019	816.1	477.1	1814.7	61.1
	2020	1578.6	499.0	2251.5	76.5
Synthetic fertilizer[a]					
	2016	118.7	25.6		
	2017	152.7	29.2		
	2018	229.3	34.1	170.8	
	2019	217.3	13.6		
	2020	214.9	29.2		
	2021	180.9	26.3		

[a] Synthetic fertilizer consisted of urea (N), monoammonium phosphate (N, P) or potassium chloride (K)

of elements via inductively coupled plasma optical emission spectrometry (Perkin Elmer Optima 7300 DV, Perkin Elmer, Waltham, MA). Manure properties measured over the study period are provided in Table 1. The amount of manure nutrients applied by treatment and year are shown in Table 2. The average manure total N, P, K application rates ranged from 611 to 1579 kg N ha^{-1}, 265 to 477 kg P ha^{-1}, and 1429 to 2252 kg K ha^{-1}, respectively. Cumulative application rates over the study were 5743 kg N ha^{-1}, 2452 kg P ha^{-1}, and 10,293 kg K ha^{-1}.

Soil sampling and analyses

Preplant samples were collected prior to corn planting each spring to determine fertilizer application rates. A total of 5 subsamples were taken per plot from 0–30 cm and 30–60 cm using a 5.1 cm soil auger. Subsamples were thoroughly mixed and composite samples were analyzed for each depth. Additional soil samples (5 subsamples per plot) were collected at the same time from 0–15 cm for enzyme analyses. Field moist subsamples were sieved and portioned immediately into a clean, sealable plastic bag and refrigerated at 5°C. Enzyme assays for β-glucosidase, β-glucosaminidase, and alkaline phosphatase were performed on air-dried soils according to Dungan et al. (2022).

Prior to chemical analysis, the remaining subsampled soils were air dried, ground and sieved using a 2 mm sieve mesh. Dried soils were analyzed for plant-available N (NO_3-N and NH_4-N) using QuickChem Methods 12–107-06–2-A (NH_4) and 12–107-04–1-B (NO_3) on a Lachat automated analyzer (Lachat Instruments 1996). Total C and N content and total elements (P, K, Ca, Mg, Zn, Mn, Na and Fe) were determined using the same methods previously referenced above. Plant available P (Olsen P) was determined via $NaHCO_3$ extraction following the procedures of Olsen et al. (1954). Soil pH was determined in a 1:1 soil–water mixture (Thomas 1996). Soil organic carbon was measured using the Walkley–Black spectrophotometric microplate method (Bierer et al. 2020). As this study was focused on plant nutrient uptake and forage quality, we only included the pre-plant soil analyses for 2021 in Table 3 for reference.

Table 3 Preplant soil nutrient concentrations in 0–30 cm depth in spring of 2021

		SOC[a]	TN[b]	TP[b]	K	Mg	Ca	NH_4-N	NO_3-N	Olsen P	Mn	Na	Zn	pH
		%	g kg^{-1}					mg kg^{-1}						
	CT[c]	13.4	1.3	1.2	4.2	13.6	62.0	3.3	22.7	126.1	419.7	449.9	76.2	8.0
	MT	13.4	1.3	1.1	4.1	14.0	65.8	3.0	14.7	125.4	406.1	391.2	69.8	8.2
	p-value	*n/s*	*n/s*	*n/s*	*n/s*	*n/s*	*n/s*	*n/s*	***	*n/s*	*n/s*	*n/s*	*n/s*	*n/s*
	MD	19.3a	1.8a	1.4a	5.0a	13.5	61.8b	2.9ab	22.7	226.9a	420.1	540.4a	81.3a	8.0
	MF	19.7a	2.0a	1.4a	5.4a	13.4	60.6b	2.6b	42.5	255.4a	419.4	544.9a	81.1a	8.1
	SD	7.1b	0.7b	0.9b	3.1b	13.9	66.7a	3.6a	2.8	10.1b	408.8	302.0b	64.0b	8.1
	SF	7.4b	0.7b	0.9b	3.1b	14.3	66.6a	3.5a	6.8	10.6b	403.4	294.9b	65.6b	8.2
	p-value[d]	***	***	***	***	*n/s*	*	**	***	***	*n/s*	***	***	*n/s*
CT	MD	19.1	1.9	1.4	5.0	13.2	59.0	3.1	25.0 b	233.1	422.8	589.0	85.1	7.8
	MF	19.0	1.9	1.4	5.4	13.4	58.7	2.8	56.5 a	245.2	426.9	592.2	83.3	8.1
	SD	7.6	0.8	0.9	3.2	13.5	64.4	3.8	2.0 c	13.0	419.0	312.8	68.4	8.0
	SF	7.7	0.8	0.9	3.1	14.2	66.1	3.5	7.5 c	13.1	410.3	305.6	68.0	8.1
MT	MD	19.4	1.7	1.4	4.9	13.9	64.6	2.6	20.5 b	220.7	417.3	491.8	77.6	8.2
	MF	20.4	2.1	1.5	5.3	13.5	62.5	2.4	28.6 b	265.7	412.0	497.6	78.9	8.2
	SD	6.7	0.7	0.9	3.0	14.2	69.1	3.4	3.7 c	7.2	398.5	291.2	59.7	8.2
	SF	7.1	0.7	0.9	3.1	14.4	67.0	3.5	6.1 c	8.1	396.5	284.2	63.2	8.2
	p-value	*n/s*	*n/s*	*n/s*	*n/s*	*n/s*	*n/s*	*n/s*	***	*n/s*	*n/s*	*n/s*	*n/s*	*n/s*

[a] Letters within column and group denote significant differences at $p < 0.05$. [b] Total N (TN) and Total P (TP). [c] Treatment codes are as follows: *CT* Conventional tillage; *MT* Minimal tillage; *M* Manure; *S* Synthetic fertilizer; *D* Winter double crop; *F* Winter fallow. [d] Significant differences in model statistics denoted as *, **, and *** for $p < 0.05$, $p < 0.01$, and $p < 0.0001$, respectively

Plant tissue sampling and analysis

Silage corn yield and samples for plant tissue analysis were collected within one week prior to bulk harvest by hand sampling 3 m of two corn rows in 2016 and 2017 or using a 2-row research plot harvester (Haldrup M-63) to harvest 10 m in 2018–2021. For triticale, a 10-m long strip was harvested with a 1.5-m wide Almaco (Nevada, IA, USA) plot harvester in 2016–2018 and 0.9-m wide harvester (RCI Engineering 36A) in 2019–2021. Plot harvest dates for corn and triticale are reported in Table S1 and were typically within one week of bulk harvest. Collected plant tissue was dried at 60 ℃ until mass did not change and ground to 2 mm using a Wiley Mill (Thomas Scientific, Swedesboro, NJ).Total C and N content and total elements (P, K, Ca, Mg, Zn, Mn, Na and Fe) were determined using the same methods previously referenced above. Forage quality parameters for both corn silage and triticale forage were determined by Dairyland Laboratories Inc. (Arcadia, WI). Corn silage and triticale collected from 2016–2021 was analyzed for acid detergent fiber (ADF), neutral detergent fiber (aNDF), lignin, starch, ether extract fat (EE), and Ohio Agricultural Research and Development Center (OARDC) energy calculations for net energy for lactation (NE_L). Triticale samples collected in 2018 and 2019 were not analyzed for forage quality due to limited available biomass. Crude protein content was calculated as follows (Ball et al. 2001):

$$\%N^*6.25 = CP$$

Statistical analysis

Analyses were performed based on the split-block design where tillage (CT, MT) were the main plots and treatments (MD, MF, SD, SF) were the sub-plot factor with four replicate blocks. Tillage and treatment were analyzed as fixed effects, and block and year were treated as random effects as cumulative treatment effects were the goal of the study. Soil, crop yield, and plant nutrient data were analyzed using generalized linear mixed modelling in PROC GLIMMIX in SAS version 9.4 (SAS Institute, Inc., 2020, Cary, NC). Mean separations were performed using Tukey's HSD at the $P < 0.05$ level. Triticale removal rates were ln-transformed to address violations in residual homogeneity of variances, and data was back-transformed for ease of discussion.

Results

Soil nutrient status

Soil nutrient concentrations for the 0–30 cm depth in spring of 2021 are reported in Table 3. There was no significant main effect of tillage; however, treatment was significant for SOC, NH_4-N, total N, Olsen P, and the following total elements (P, K, Ca, Na, and Zn). There was a significant interaction between treatment and tillage for soil NO_3-N. Following 6 years of manure application, manured plots had greater SOC (63%), total N (61%), Olsen P (96%), total P (36%), total K (40%), total Na (45%) and total Zn (20%) compared to the plots receiving synthetic fertilizer only. Alternatively, manured plots had lower NH_4-N (26%) and total Ca (9%) compared to plots receiving synthetic fertilizer only. Greater soil NO_3-N was found in manured treatments, compared to synthetic fertilizer treatments, with no difference between cover crop and fallow in the minimum tillage treatments. However, there was 2.3 times greater NO_3-N in the conventionally tilled manure plots that were left fallow as opposed to having triticale. The synthetic fertilizer plots did demonstrate this same trend, but the difference was not significant.

Soil health measurements taken in 2018, 2019, and 2021 showed a significant increase in enzyme activity associated with C, N, and P cycling with manure application, regardless of winter cover crop or tillage (Table 4). After six years, manure application increased β-glucosidase, β-glucosaminidase, and alkaline phosphomonoesterase by 69%, 75%, and 45%, respectively.

Yield and tissue nutrient concentrations

Average yields (Mg ha^{-1}) and tissue nutrient concentrations for corn silage are reported in Table 5, with yields being adjusted to a standard moisture content of 65%. There was a significant effect of tillage on tissue P concentration only, with the minimum tillage treatments being greater than the conventionally tilled treatments. There was a significant effect of treatment on corn yield and tissue C, N, P, K, Mg, Ca, and Na, and significant

Table 4 Average microbial enzyme activities in the 0–15 cm soil depth pooled over 2018, 2019, and 2021[ab]

		β- Glucosidase	β-Glucosaminidase	Phosphomonoesterase
		μg pN g^{-1} dry soil hr^{-1}		
	CT[c]	160.5	34.4	187.9 a
	MT	108.2	23.5	135.0 b
	MD	192.8	45.8 a	214.8 a
	MF	184.3	42.8 a	153.3 a
	SD	68.1	11.6 b	109.8 b
	SF	92.3	15.7 b	167.8 b
CT	MD	210.2 a	50.8	215.7
	MF	239.1 a	52.3	194.5
	SD	72.0 c	12.9	116.4
	SF	120.7 c	21.7	225.0
MT	MD	175.4 a	40.7	214.0
	MF	129.5 b	33.2	112.2
	SD	64.2 c	10.4	103.2
	SF	63.8 c	9.7	110.7

[a] Letters within column and group denote significant differences. [b] Samples were collected in the spring in 2018 and in the fall for 2019–2020. [c] Treatment codes are as follows: *CT* Conventional tillage; *MT* Minimal tillage; *M* Manure; *S* Synthetic fertilizer; *D* Winter double crop; *F* Winter fallow

interactions between tillage and treatment for tissue Mg, Ca, Na, Mn and Fe. Of the significant interactions, Tukey's adjusted least squared means detected significant differences for only Mg and Na. Manure application with winter fallow had the greatest yield (53 Mg ha^{-1}) and was statistically similar to the synthetic fertilizer treatment with winter fallow. Yields were lower in both manure and synthetic fertilizer treatments (50 Mg ha^{-1}) with winter triticale, although they were also similar to the synthetic fertilizer treatment with fallow. Silage tissue N, P, and K concentrations were 12, 21, and 36% greater with manure application vs synthetic fertilizer, respectively, irrespective of winter triticale or fallow. Both Mg and Ca silage tissue concentrations were lower in plots receiving manure vs synthetic fertilizer (21 and 24%, respectively) irrespective of winter triticale or fallow. In conventionally tilled treatments, silage Na tissue concentrations were greater with manure than synthetic fertilizer treatment, however these trends were less clear in the minimum tillage treatments with MF being greater than SD.

Average yields (Mg ha^{-1}) and tissue nutrient concentrations for triticale are reported in Table 6, with yields being adjusted to a standard moisture content of 70%. There was a significant effect of tillage on yield and tissue Na, with both being greater under conventional tillage. Manure application significantly influenced triticale yield and all tissue nutrient concentrations, and there was a significant interaction of tillage with treatment for tissue Mg, Ca, Na, and Mn concentrations. Manure application had the greatest yield (17.2 Mg ha^{-1}) and increased tissue N, P, K, and Fe by 31%, 45%, 45%, and 9% respectively, compared to synthetic fertilizer. Tissue Mg, Na, and Zn concentrations were lowest in synthetic fertilizer and did not differ between tillage treatments. On manured plots, tissue Mg, Na, and Zn concentrations were 10%, 38%, and 28% greater, respectively, with conventional tillage vs minimum tillage. Tissue Ca and Mn concentrations were greatest in synthetic fertilizer under minimum tillage and generally, were lower in manured plots. However significant trends differed by tillage type. Under conventional tillage, tissue Ca and Mn were not significantly different between manured vs synthetic fertilizer, but increased by 25% and 21%, respectively, with synthetic fertilizer under minimum tillage.

Nutrient removal rates

Corn silage nutrient removal rates are reported in Table 7. Corn silage nutrient removal significantly differed between treatments but exhibited no response to or interactions with tillage. Manure application significantly influenced nutrient removal rates for all but corn tissue Zn and Mn. Regardless of cover crop presence, manure application increased N, P, K, and Na removal by 15%, 25%, 37%, and 15%, respectively, whereas Mg and Ca removal decreased by 19% and 20%, respectively. While there was no difference in Zn removal with the inclusion of triticale, the Zn removal in fallow plots with manure was 13% greater than with synthetic fertilizer and fallow. Removal rates for Fe were greatest with manure application with winter fallow, significantly increasing removal

Table 5 Average corn silage tissue nutrient concentrations pooled over 2016 -2021. Yield reported at standard moisture of 65%

		Yield[a]	N	P	K	Mg	Ca	Na	Zn	Mn	Fe
		Mg ha^{-1}	%	g kg^{-1}				mg kg^{-1}			
	CT[c]	51.4	1.2	2.0b	9.7	2.1	2.8	191.1	36.7	50.0	170.2
	MT	51.2	1.2	2.1a	9.6	2.1	2.7	195.6	37.7	49.2	164.0
	p-value[b]	*n/s*	*n/s*	*	*n/s*	*n/s*	*n/s*	*n/s*	*n/s*	*n/s*	*n/s*
	MD	50.4b	1.3a	2.3a	11.8a	1.9	2.4b	205.3	37.5	49.0	167.8
	MF	53.0a	1.2a	2.3a	11.7a	1.9	2.5b	209.1	38.3	49.4	169.0
	SD	50.5b	1.1b	1.8b	7.5b	2.4	3.1a	176.4	37.6	50.7	165.9
	SF	51.2ab	1.1b	1.8b	7.7b	2.3	3.0a	182.6	35.3	49.4	165.8
	p-value	**	***	***	***	***	***	***	*n/s*	*n/s*	*n/s*
CT	MD	50.3	1.2	2.3	12.0	1.9c	2.6	213.4ab	38.2	51.4	175.9
	MF	52.8	1.3	2.2	11.6	1.9c	2.5	201.1abc	37.5	48.6	176.9
	SD	50.7	1.1	1.7	7.7	2.3ab	3.1	171.2d	35.7	51.0	167.8
	SF	51.6	1.1	1.7	7.6	2.2b	3.0	178.7d	35.5	49.1	160.4
MT	MD	50.4	1.3	2.3	11.6	1.8c	2.3	197.1abcd	36.9	46.6	159.7
	MF	53.2	1.2	2.3	11.8	1.9c	2.4	217.2a	39.2	50.2	161.1
	SD	50.4	1.1	1.8	7.2	2.4a	3.1	181.6cd	39.6	50.3	164.1
	SF	50.8	1.1	1.9	7.7	2.3ab	3.0	186.4bcd	35.1	49.8	171.2
	p-value	*n/s*	*n/s*	*n/s*	*n/s*	*	*	*	*n/s*	*	*

[a]Letters within column and group denote significant differences. [b]Significant differences in model statistics denoted as *, **, and *** for $p<0.05$, $p<0.01$, and $p<0.0001$, respectively. [c]Treatment codes are as follows: *CT* Conventional tillage; *MT* Minimal tillage; *M* Manure; *S* Synthetic fertilizer; *D* Winter double crop; *F* Winter fallow

Table 6 Triticale tissue nutrient concentrations pooled over 2016–2021. Yield reported at standard moisture of 70%

		Yield[a]	C	N	P	K	Mg	Ca	Na	Zn	Mn	Fe
		Mg ha^{-1}	%		g kg^{-1}				mg kg^{-1}			
	CT	11.0a	40.8	2.4	3.8	34.7	1.4	2.9	316.1	48.7	42.2	94.6
	MT	9.8b	40.8	2.3	3.9	33.9	1.3	2.9	208.5	47.6	41.8	94.6
	p-value[b]	**	*n/s*	*n/s*	*n/s*	*n/s*	*n/s*	*n/s*	*	*n/s*	*n/s*	*n/s*
	MD	17.2a	40.4b	2.8a	4.9a	44.2a	1.5	2.6	456.3	57.4	38.5	98.7
	SD	3.6b	41.2a	1.9b	2.7b	24.3b	1.2	3.2	68.3	38.9	45.5	90.4
	p-value	***	***	***	***	***	***	***	***	***	***	*n/s*
CT	MD	17.7	40.4	2.9	5.0	45	1.5a	2.8bc	562.0a	60.7a	40.1bc	97.9
	SD	4.4	41.2	1.9	2.6	24.4	1.2c	3.0ab	70.3c	36.6c	44.3ab	91.3
MT	MD	16.7	40.4	2.7	4.9	43.5	1.4b	2.5c	350.6b	54.0b	36.9c	99.6
	SD	2.9	41.2	2.0	2.9	24.2	1.3c	3.3a	66.3c	41.2c	46.7a	89.5
	p-value	*	*n/s*	*	*n/s*	*n/s*	***	**	*n/s*	**	*	*n/s*

[a]Letters within column and group denote significant differences. [b]Significant differences in model statistics denoted as *, **, and *** for $p<0.05$, $p<0.01$, and $p<0.0001$, respectively. [c]Treatment codes are as follows: *CT* Conventional tillage; *MT* Minimal tillage; *M* Manure; *S* Synthetic fertilizer; *D* Winter double crop; *F* Winter fallow

Table 7 Average nutrient removal rate for corn silage and triticale pooled over 2015–2021

		N[a] kg ha^{-1}	P	K	Mg	Ca	Na	Zn	Mn	Fe
Corn										
	MD[c]	267.1a	52.8a	262.9a	40.3b	52.1b	4.5a	0.80ab	1.06	3.51ab
	MF	277.9a	53.5a	271.4a	42.7b	57.4b	4.6 a	0.90a	1.14	3.75a
	SD	231.6b	39.5b	163.6b	49.6a	65.6a	3.8 b	0.78ab	1.09	3.36b
	SF	234.3b	40.9b	171.1b	48.9a	66.1a	4 b	0.75b	1.08	3.53ab
	p-value[b]	***	***	***	***	***	***	*	*n/s*	*
Triticale										
	CT	81.0	14.3	127.2	4.7	8.9 a	1.4	0.17	0.13	0.28
	MT	66.8	12.5	110.6	3.8	7.1 b	0.9	0.13	0.10	0.25
	p-value	*n/s*	*n/s*	*n/s*	*n/s*	*	*	*n/s*	*n/s*	*n/s*
	MD	128.8a	24a	212.6a	7.3a	13a	2.2	0.27a	0.18a	0.44a
	SD	19.0b	2.9b	25.2b	1.2b	3.0b	0.1	0.04b	0.04b	0.09b
	p-value	***	***	***	***	***	***	***	***	***
CT	MD	139.2	25.4	223.9	8.0	14.3	2.8 a	0.29	0.20	0.45
	SD	22.7	3.3	30.6	1.5	3.5	0.1 c	0.04	0.05	0.10
MT	MD	118.4	22.7	201.4	6.7	11.7	1.7 b	0.24	0.17	0.43
	SD	15.2	2.4	19.7	1.0	2.5	0.1 c	0.03	0.04	0.07
	p-value	*n/s*	*n/s*	*n/s*	*n/s*	*n/s*	*	*n/s*	*n/s*	*n/s*

[a]Letters within column and group denote significant differences. [b]Significant differences in model statistics denoted as *, **, and *** for $p<0.05$, $p<0.01$, and $p<0.0001$, respectively. [c]Treatment codes are as follows: *CT* Conventional tillage; *MT* Minimal tillage; *M* Manure; *S* Synthetic fertilizer; *D* Winter double crop; *F* Winter fallow

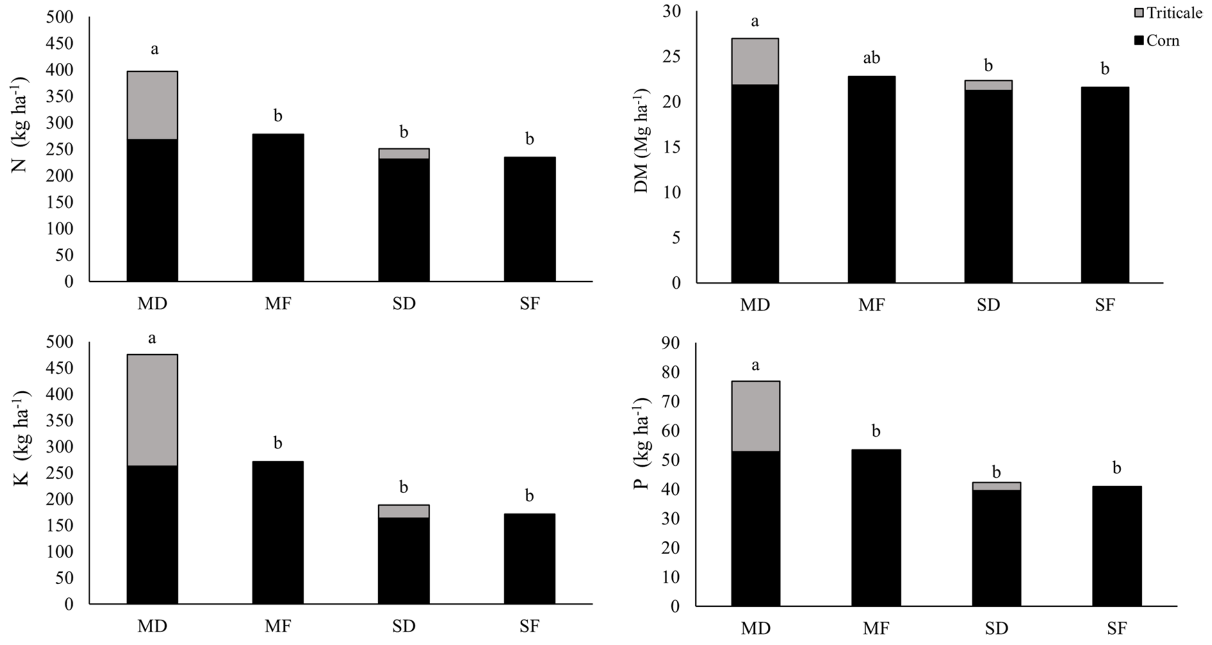

Fig. 2 Average annual NPK removal and dry matter [DM] production by treatment and pooled from 2016–2021. [c]Treatment codes are as follows: Manure (M), Synthetic Fertilizer (S), Winter Double Crop (D), Winter Fallow (F)

Table 8 Average forage quality for corn silage pooled over 2015–2021 and triticale pooled over 2017–2021[a]

		CP[b]	ADF	aNDF	Lignin	Starch	Fat	NE_L
		%						
Corn								
	CT	7.3	23.4	40.0	2.5a	30.2	2.1	72.8b
	MT	7.4	23.1	39.7	2.4b	30.3	2.1	73.5a
	p-value[c]	*n/s*	*n/s*	*n/s*	*	*n/s*	*n/s*	*
	MD	7.9a	23.1b	39.6ab	2.4ab	28.6b	2.2a	73.5ab
	MF	7.8a	23.0b	39.5b	2.6a	30.2ab	2.2a	72.6ab
	SD	6.9b	24.1a	41.1a	2.6ab	30.3ab	2.0b	72.5b
	SF	6.9b	22.9b	39.2b	2.3b	31.8a	2.1ab	73.9a
	p-value	***	**	*	*	***	**	*
Triticale								
	CT	12.9	30.2	50.0	1.8	0.3	2.5	66.1
	MT	13.5	30.0	49.8	1.8	0.3	2.6	66.6
	p-value	*n/s*	*n/s*	*n/s*	*n/s*	*n/s*	*n/s*	*n/s*
	MD	15.2a	31.7a	52.6a	2.0a	0.2	2.7a	63.6b
	SD	11.2b	28.5b	47.3b	1.6b	0.4	2.5b	69.2a
	p-value	***	***	***	***	*n/s*	**	***
CT	MD	15.4	31.3	52.2	1.9	0.3	2.7	63.6
	SD	10.4	29.0	47.9	1.7	0.3	2.4	68.6
MT	MD	15.0	32.0	53.0	2.1	0.2	2.7	63.6
	SD	11.9	28.0	46.7	1.5	0.4	2.6	69.7
	p-value	*	*	*n/s*	**	*n/s*	*n/s*	*n/s*

[a] Letters within column and group denote significant differences. [c] Significant differences in model statistics denoted as *, **, and *** for $p < 0.05$, $p < 0.01$, and $p < 0.0001$, respectively. [b] Treatment codes are as follows: *CT* Conventional tillage; *MT* Minimal tillage; *M* Manure; *S* Synthetic fertilizer; *D* Winter double crop; *F* Winter fallow; *CP* Crude protein; *ADF* Acid detergent fiber; *aNDF* Neutral detergent fiber; NE_L Net energy for lactation

by 10% compared to synthetic fertilizer with winter triticale.

Triticale removal rates are reported in Table 7. Significant effects of tillage occurred for Ca and Na removal, with removal rates being greatest with conventional tillage. Treatment differences were detected for removal rates of all nutrients, and significant interaction of tillage with treatment occurred only for Na. Removal rates for all nutrients increased by 77–97% with manure application vs synthetic fertilizer. Sodium (Na) removal rates were lowest for synthetic fertilizer regardless of tillage but increased by 39% with conventional (vs minimal tillage) in manured plots.

Average annual DM production and NPK removal are shown in Fig. 2. Winter triticale added an additional 5.2 and 1.1 Mg DM ha^{-1} with manure and synthetic fertilizer, respectively. For both manure application and synthetic fertilizers, winter triticale treatments removed 1.1–1.8 times as much N, P, and K as winter fallow treatments.

Forage quality

Significant differences in silage corn forage quality were detected for both tillage practice and treatments (Table 8). Conventional tillage increased lignin by 5% and decreased NE_L by 1%. Manure application increased silage corn CP by 11% compared to synthetic fertilizer, regardless of winter triticale. Fat content increased by 6% with manure application, with or without winter triticale, compared to synthetic fertilizer with winter triticale. For winter fallow plots, lignin increased by 9% with manure application vs synthetic fertilizers. Synthetic fertilizer with winter triticale had the greatest ADF and aNDF and were 5% and 4% greater than synthetic fertilizer with winter fallow treatments, while there were no differences in manured treatments. The combination of winter fallow and synthetic fertilizer increased starch content by 10% compared to manure with winter triticale, and increased NE_L by 2% compared to synthetic fertilizer with winter triticale.

For triticale, significant differences between treatments occurred for all quality parameters except starch, and significant interactions with tillage occurred for CP, ADF, and lignin (Table 8). Although there were significant interactions in the model, these were not differentiated with the Tukey's HSD. Manure application increased CP, ADF, aNDF, lignin, and fat content by 27%, 10%, 10%, 20%, and 8% compared to synthetic fertilizer, and decreased NE_L by 9%.

Discussion

Preplant soil data

Following six years of manure application, there was a significant increase in all soil nutrients except Ca and Mn. Long-term manure applications have been shown to increase soil nutrient concentrations as a result of the high concentrations of N, P, K, and various micronutrients found in manure (Bierer et al. 2022; Butler and Muir 2006; Edmeades 2003). Thus, the increased nutrient concentration with manure application seen in this study are not unexpected. Neither tillage nor cover crop had an influence on soil nutrient status except for NO_3-N. The inclusion of triticale decreased soil NO_3-N in conventionally tilled plots that had received manure by 56%, compared to conventionally tilled manured plots that were fallow, which reduces the NO_3-N available for loss via leaching over the winter (Salmerón et al. 2010). While not statistically significant, triticale inclusion did lower soil NO_3-N to a lesser degree on minimally tilled plots that received manure. Although there was no significant effect of tillage on soil nutrient status (except for NO_3-N), it is important to note that in the MT plots with manure application there was a buildup of manure at the surface (~5 + cm). It is likely that incorporation of the manure enhanced N mineralization, leading to higher NO_3-N concentrations in the conventionally tilled plots which was taken up by the triticale. Additionally, the use of conventional tillage may have increased N availability deeper in the soil profile improving accessibility for uptake by the triticale (Maher et al. 2022). There may also have been some losses of N as ammonia in the minimally tilled plots as there was no incorporation of manure, which could have reduced the overall N available for mineralization in those plots, although there were no significant differences due to tillage in manured plots with winter triticale.

Soil SOC was 2.5 times greater in manured vs. synthetic fertilizer plots with no effect of tillage or inclusion of winter triticale. Although several studies have reported enhanced C sequestration and buildup of SOC with reduced tillage and cover crops (Aguilera et al. 2013; Angers and Eriksen-Hamel 2008; Bolinder et al. 2020; Jian et al. 2020; Poeplau and Don 2015; West and Post 2002), these same trends were not observed in the current study. As the triticale was harvested for forage, there was little residue left in the plots which may explain why enhanced SOC was not observed. Manure application also enhanced soil microbial activity with increased activities of β-glucosidase (associated with OM decomposition and C-cycling), β-glucosaminidase (associated with C- and N-cycling), and alkaline phosphomonoesterase (associated with P-cycling). Enhanced microbial enzyme activity with manure application has been reported in other studies and has been associated with increased OM mineralization (Fang et al. 2005; Gautam et al. 2020; Lupwayi et al. 2019; Miransari 2013; Ozlu et al. 2019). The increased OM mineralization leads to greater soil nutrient concentrations over time, enhancing the pool of plant-available nutrients for crop uptake.

Yield and tissue nutrient concentrations

Corn silage yields showed little influence of tillage, manure application, or winter double crop which is not surprising as all treatments were supplied with sufficient nutrients for growth. The slight increase in yield with winter fallow and manure application compared to both winter double crop treatments could be due to reduced soil moisture and plant available N in the spring (Mitchell and Teel 1977; Reese et al. 2014). Soil water storage was measured on these plots from 2016 to 2021 and was lower in the manure treatment with winter triticale compared to the other treatments in the spring each year, due to winter/spring water use by the triticale (Yost et al. 2022). Although these plots are irrigated, there is potential that decreased moisture at planting could have affected germination and early growth (Mitchell and Teel 1977; Reese et al. 2014). Reese et al. (2014) found that large winter wheat (*Triticum aestivum* L.) yields (>2000 kg ha^{-1}) reduced subsequent corn yields when subjected to moderate water stress. Under these conditions, cover crop growth is not limited, but water uptake by the cover crop reduces water availability for the following crop. However, even with a slight corn silage yield decrease in the manure with triticale treatment, the overall forage production (corn silage + triticale) was 28% greater than with manure and fallow.

Although yields were not different in corn silage, there was enhanced tissue concentrations and removal of N, P, and K in treatments with manure. Triticale yields and tissue N, P, and K were higher with manure, both contributing to greater plant uptake. Other studies have reported this same trend along with significant increases in NPK status in soil with long term manure application (Bierer et al. 2022; Butler and Muir 2006; Moore et al. 2014; Thomas et al. 2019). The enhanced nutrient uptake of NPK with the corn and triticale likely stems from the large pool of these nutrients provided by the fall manure applications compared to the synthetic fertilizer (Butler and Muir 2006; Muir et al. 2001). In addition, the increase in SOC (and associated nutrients) with manure application may provide a slow-release fertilizer over time, enabling plants to take up more nutrients over the growing season compared to synthetic fertilizer. Increased microbial activity may also increase plants' ability to take up nutrients through the production of key enzymes involved in mineralization of organically bound nutrients and plant–microbe interactions influencing root zone exudates involved in nutrient uptake (Miransari 2013).

Manure additions decreased Ca tissue concentrations in corn silage and triticale compared to synthetic fertilizer treatments. Tissue concentrations of Mg were also lower in corn silage with manure application vs synthetic fertilizer only. Other studies have reported depressed Ca and Mg tissue concentrations with manure application relative to synthetic fertilizer treatment (Bierer et al. 2022; Parsons et al. 2007; Warman and Cooper 2000). Manure addition reduced soil Ca (9%) and increased soil K (40%) which may have induced competitive uptake of K over Mg and Ca. Parsons et al. (2007) reported that K^+ and Ca^{2+} antagonism in plots receiving liquid dairy manure resulted in depressed wheat tissue Ca in a corn-wheat rotation. Nonspecific antagonisms in plant uptake between K^+ and Ca^{2+} or Mg^{2+} have been reported to occur on root plasma membrane and cytoplasm for maintenance of intracellular electrical charge (Marschner 2012). In contrast to silage corn, triticale had greater tissue Mg concentration in manure vs. synthetic fertilizer treatments. Triticale has been shown to have greater translocation of Mg from roots to aboveground vegetation (Mugwira 1980), which may explain the increased triticale tissue Mg with manure application that was not seen with corn silage. Manure plots that were conventionally tilled also had greater triticale tissue Na, and Zn concentrations than plots with manure receiving minimum tillage, which is likely due to the accumulation of manure at the surface in MT plots reducing the availability of micronutrients within the zoot zone (Farmaha et al. 2022).

Nutrient removal rates

From a nutrient management perspective, one of the advantages of using a winter double crop is the potential to mine excess nutrients from the soil, particularly in regularly manured fields. In this study, nutrient removal rates for both corn silage and triticale responded strongly to manure application, regardless of tillage and (in case of corn silage) cover crop presence. Although there were few differences in silage corn yield, there was an increase in tissue concentrations of N, P and K with manure application which resulted in greater removal rates (15–37% greater N, P K removal). The triticale had both greater biomass production as well as greater N, P, K tissue concentrations with manure addition, compared to synthetic fertilizer only, resulting in greater nutrient removal. Overall, inclusion of triticale in manured treatments removed an additional 129 and 24 kg ha^{-1} of N and P, respectively. However, there still remained high levels of soil N and P in the spring, suggesting that inclusion of a winter crop alone cannot offset increasing soil nutrients with continuous manure application at high rates. Although synthetic fertilizer treatments did not see as much of an effect, winter triticale still removed an additional 18% of applied N and 26% of applied P. This is in-line with data presented by Brown (2006), which showed that double crop systems can increase cumulative P uptake and removal by 30–42%. In the present study, the differences in response to winter triticale between manure and synthetic fertilizer are due to the fact that the synthetic fertilizer only plots did not receive any fall nutrients. Although careful manure management is still necessary when considering tradeoffs of additional fall nutrients, winter triticale exhibits potential for removing excess nutrients in fields with historical manure applications and may help producers meet nutrient management goals.

Forage quality

Forage quality is determined by a variety of factors including palatability, intake, digestibility, nutrient content, potential detrimental impacts on animal health, and overall animal performance (Allen 1996; Ball et al. 2001; Shewmaker et al. 2005; NRC 2001). In general, the more desirable forages have lower ADF, NDF and lignin content thus promoting greater intake and digestibility, and greater percentages of the energy-producing compounds CP, WSC, and EE (Arispe and Filley 2016; Ball et al. 2001; NRC 2001). In this study, manure application increased ADF by 1% and 3%, and aNDF by 2% and 5% thereby decreasing NE_L 1% and 6% for corn silage and triticale, respectively. As NDF and ADF concentrations increase, the predominant energy constituents subsequently decrease, which likely explains the reduced NE_L seen in this study (Moore et al. 2020). The CP content of both corn silage and triticale were greater in manured vs synthetic fertilizer treatments as N uptake was enhanced (see discussion above). Increasing CP content with manure application has been widely reported, but response of fibrous components is highly variable (Bierer et al. 2022; Delevatti et al. 2019; Min et al. 2002; Moore et al. 2020; Muir et al. 2001). Bierer et al. (2022) reported similar trends with manure application and increased CP, but did not see treatment differences for ADF, NDF, or NE_L. Min et al. (2002) report similar findings of increased CP content in alfalfa-grass mixtures with dairy slurry applications compared to control but suggested grass species had greater impact on ADF and NDF content than manure addition.

From an animal health perspective, balancing nutrient concentrations in feed rations is critical for preventing detrimental metabolic conditions and diseases. For both corn silage and triticale, manure application resulted in significantly greater concentrations of forage K. Large concentrations of forage K have been associated with both milk fever (a metabolic disorder due to K:Ca antagonism) and grass tetany (degradation of the nervous system due to K:Mg antagonism) in dairy cows, and is thus a major concern for animal producers when considering sources of animal feed (Horst et al. 1997; Ishler et al. 2016; Littledike et al. 1981; Moore et al. 2020; Oetzel 2011). Ishler et al. (2016) reported that K concentrations exceeding 1.2% (DM basis) increase the risk of such diseases. In the current study, all the triticale from M plots exceeded this level 3.7-fold, suggesting that careful blending of triticale with other feed ingredients in the mixed ration may be necessary to avoid health risks.

In summary, significant differences in tissue concentrations, nutrient removal, and forage quality for both corn silage and triticale forage primarily resulted between six years of manure and synthetic fertilizer application. The application of manure increased forage tissue N, P, and K concentrations as well as removal, compared to synthetic fertilizer alone. If considered from a nutrient mining standpoint, use of triticale as a winter double crop has potential for adding significantly to annual nutrient removal rates. However, nutrient additions may be necessary for adequate plant growth in fields without a history of manure and producers should carefully consider the trade-offs of late season fertilizer additions. The addition of manure decreased forage digestibility through increases in ADF, aNDF and lignin, but increased CP. As commonly seen with forages grown on heavily manured soils, triticale may be at increased risk of excess K tissue concentrations that can be detrimental to animal health. However, resulting imbalances can be mitigated through well-balanced feed rationing.

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conclusions in this publication are those of the authors and should not be construed to represent any official USDA or U.S. Government determination or policy. USDA is an equal opportunity provider and employer.

Author contributions Study conception and design was prepared by David Bjorneberg, Robert Dungan, and April Leytem. Material preparation, data collection and analysis were performed by all authors. The first draft of the manuscript was written by Abigail Baxter and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

Data availability The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request.

Declarations

Conflict of interest The authors declare no conflict of interest.

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