Winter Rye Cover Crop Management Influences on Soil Water, Soil Nitrate, and Corn Development

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ABSTRACT

A winter rye (*Secale cereale* L.) cover crop can be seeded after corn (*Zea mays* L.) silage to mitigate some of the environmental concerns associated with corn silage production. Rye can be managed as a cover crop by chemical termination or harvested for forage. A field study was conducted in Morris, MN in 2008 and 2009 to determine the impact of killed vs. harvested rye cover crops on soil moisture and NO_3–N, and to monitor the impact of the rye on subsequent corn yield. Corn for silage was seeded either after winter fallow (control), after a rye cover crop terminated 3 to 4 wk before corn planting (killed rye), or after a rye forage crop harvested no more than 2 d before corn planting (harvested rye). Soil moisture after killed rye was similar to the control, but after harvested rye was 16% lower. Available soil NO_3–N was decreased after both killed rye (35%) and harvested rye (59%) compared to the control. Corn biomass yield after killed rye was similar to the control, but yield following harvested rye was reduced by 4.5 Mg ha^{-1}. Total forage biomass yield (silage + rye) was similar for all treatments. This work demonstrates that the environmental benefits of a winter rye cover crop can be achieved without impacting corn yield, but the later termination required for rye forage production resulted in soil resource depletion and negatively impacted corn silage yield.

Winter rye is a recommended cover crop in cold climates as it is winter hardy and is able to begin regrowth early in the spring (Stoskopf, 1985). Rye is also a good choice when the cover crop is harvested for spring forage because it reaches optimum growth stage sooner than other small grains (Maloney et al., 1999). In the Upper Midwest region of the United States, rye has been shown to scavenge excess soil NO_3–N (Jewett and Thelen, 2007) and reduce NO_3–N leaching (Kaspar et al., 2007; Strock et al., 2004). Increased ground cover provided by the rye may also reduce soil erosion (Kaspar et al., 2001), while rye biomass may help maintain soil organic matter (Kaspar et al., 2006). These environmental benefits make rye particularly useful in dairy operations where corn silage is the primary crop and manure is often applied in the fall. However, rye can decrease profitability due to corn yield declines (Thelen and Leep, 2002), which may be one reason why adoption of rye cover crop systems has been limited (Singer et al., 2007).

The impact of rye on corn production is influenced by rye management methods (Tollenaar et al., 1992). When used as a cover crop, rye can be chemically terminated before corn planting, but timing of termination influences the subsequent impacts on corn yield. Rye termination at corn planting can result in decreased corn yield (Johnson et al., 1998; Tollenaar et al., 1992), but when terminated a week or more before corn planting, corn yield similar to (Singer et al., 2008) or slightly greater than (Duiker and Curran, 2005) corn after winter fallow has been observed. When corn yield suppression after rye has occurred, reduced soil moisture (Raimbault et al., 1991), inadequate N (Tollenaar et al., 1993), rye residue (Raimbault et al., 1991), and allelopathic effects of rye on corn (Raimbault et al., 1990; Tollenaar et al., 1992) have been cited as reasons for the corn yield decline. Rye can be terminated earlier to limit resource depletion, prevent excess rye residue, and avoid possible allelopathic effects.

When rye is used as a cover crop, environmental benefits are immediate and long-term economic benefit is gained by conserving soil resources (Reicosky and Forcella, 1998), but the economic benefit of rye as a forage is not achieved. In dairy or beef (*Bos taurus*) production systems, rye can be harvested as high quality spring forage (Maloney et al., 1999), with a balance between rye forage yield and quality being reached when rye is harvested at boot stage (Edmisten et al., 1998). When double cropped after winter rye, decreased corn yield compared to sole cropped corn has been observed, but total forage production was greater in a rye–corn silage double crop system (Raimbault et al., 1990; Tollenaar et al., 1992). The double-crop system therefore offers the potential for increased profitability.

Previous work suggests that spring rye management can dictate the effect of the cover crop on subsequent corn production. However, few data are available on soil moisture and NO_3–N depletion induced by killed vs. harvested rye and the effect of resource depletion on subsequent corn silage. We hypothesize that later rye termination in the harvested rye double crop system will result in greater resource depletion and greater impact on subsequent corn than for a killed rye cover crop. The objective of this study was to examine the feasibility of winter

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Published in Agron. J. 103:316–323 (2011)
Published online 15 Dec 2010
doi:10.2134/agronj2010.0327

rye cover cropping in a corn silage production system in Minnesota by quantifying soil moisture and soil NO_3–N depletion induced by killed or harvested rye and monitoring the effect of resource depletion on subsequent corn development and yield.

MATERIALS AND METHODS

The study was conducted at the West Central Research and Outreach Center in Morris, MN (45°35′ N, 95°52′ W, 348 masl), from September 2007 through October 2009. The soil series was Doland silt loam (fine-loamy, mixed, superactive, frigid Calcic Hapludoll). The experimental design was a randomized complete block with four replications. Treatments were corn silage seeded after winter fallow (control), corn silage seeded after a killed winter rye cover crop (killed rye), and corn silage after a harvested winter rye cover crop (harvested rye). The plot size was 18.3 by 18.3 m, 18.3 by 3.0 m, and 18.3 by 15.3 m in the control, killed rye, and harvested rye treatments, respectively. Plots were in the same location each year of the study.

Before study initiation, the experimental area was in corn silage production in 2006 and 2007. In the fall of 2006, liquid swine (*Sus scrofa*) manure was surface applied at a total N rate of 296 kg ha^{-1} and immediately incorporated with a disk chisel plow. Liquid dairy manure was injected 10 Sept. 2007 and 12 Sept. 2008 at a rate of 140,000 L ha^{-1} using a top fill slurry tanker with hydraulic disk injectors. Total N application rates were 458 kg ha^{-1} in 2007 and 424 kg ha^{-1} in 2008. Application rates were based on recommendations for continuous corn production in Minnesota (Rehm et al., 2001) and assuming a 50% first year N availability (Russelle et al., 2008) with no credit given for second year availability. Manure application rate was designed to mimic that of dairy producers who have surplus N and may apply manure at high rates. After manure injection in 2007 and 2008, the entire study area was tilled with an Ecolo-Tiger 530 disk chisel plow (Case IH, Racine, WI) with five main shanks spaced 0.76 m apart and 0.51 m front tandem disks and then field cultivated. No additional N applications were made.

The winter rye cultivar Rymin was seeded on 14 Sept. 2007 and 18 Sept. 2008 using a 2.4 m John Deere end wheel drill. Rye was seeded at a rate of 94 kg ha^{-1} in 2007 and 79 Kg ha^{-1} in 2008 at a row spacing of 19.1 cm. In the killed rye treatment, rye was terminated 25 Apr. 2007 and 28 Apr. 2008 by spraying with glyphosate at a rate of 1.3 kg a.e. ha^{-1}. Rye residue remained in the plots after termination. In the harvested rye treatment, rye was removed from the plots on 19 May 2008 and 21 May 2009 using a mechanical harvester. Glyphosate was immediately applied at a rate of 0.6 kg a.e. ha^{-1} in 2008 and 1.3 kg a.e. ha^{-1} in 2009. The combination of harvesting rye and immediate glyphosate application resulted in little rye regrowth. All plots received alachlor at a rate of 2.8 kg a.i. ha^{-1} after corn planting and glyphosate (0.6 kg a.e. ha^{-1} in 2008 and 1.3 kg a.e. ha^{-1} in 2009) in early June and early July to prevent weed growth.

Rye growth stage (Zadoks et al., 1974) and biomass were determined before soil freezing in the fall, at termination in the killed rye treatment, and at harvest in the harvested rye treatment. Fall biomass was determined only in the harvested rye treatment. Biomass yield was determined by harvesting 1 m of row from the center of each plot to a height of 0.038 m. This height was chosen to approximate the machine-harvestable portion of the aboveground biomass. One sample was collected in each plot. Samples were dried at 65°C for 72 h, and biomass yield was determined from the dry weight of the samples. Dried samples were ground to pass through a 1-mm sieve and analyzed for C and N by dry combustion using a Dumas instrument (Leco TruSpec CHN, Leco Corp., St. Joseph, MI). Carbon data are available for only rye samples collected at harvest in the harvested rye treatment. Carbon/N ratio at harvest was 13:1 in 2008 and 11:1 in 2009. Rye stubble remaining in the harvested rye treatment was highly variable. In 2009, rye stubble height was measured at three locations in each plot in the harvested rye treatment and ranged from 7 to 17 cm. Rye stubble biomass was determined by collecting 1 m of row at each point where height was measured. Rye stubble biomass averaged 1113 kg ha^{-1}.

Corn was seeded in all treatments using a four row Hiniker no-till planter on 22 May 2007 and 21 May 2008. Planting date was later than average for Minnesota, which is between mid- April and mid-May. The later planting date was chosen to allow greater rye growth in the harvested rye treatment. Corn in the control and killed rye treatments was seeded the same day as corn after harvested rye to avoid confounding planting date effects. Each year, the corn cultivar Pioneer 37Y14 was seeded at a rate of 88,180 seeds ha^{-1} for all treatments. Control plots were field cultivated before corn planting, while corn after killed and harvested rye was no-till seeded. Corn plant population was determined 4 wk after seeding in 2008 in a 1.5 m^2 area in each plot. No between treatment difference was found. Plant population was not measured in 2009. Corn growth stage (Ritchie et al., 2005) and height were determined weekly in May and June and every other week from July through September. In May and June, 10 plants were sampled per plot, with three plants per plot being sampled thereafter. Samples for corn biomass yield were collected 9 Sept. 2007 and 3 Oct. 2008. Corn biomass yield was determined by hand harvesting and weighing two 3-m sections of row within each plot. To avoid edge effects, corn yield samples were collected from the middle rows of each plot. A subsample of three plants was then dried at 65°C for 48 h for dry matter determination. Corn yield data were not available for one replication of the killed rye treatment in 2008 and one replication of the harvested rye treatment in 2009. Missing yield and dry matter data were replaced using the Missing Data Formula Technique (Gomez and Gomez, 1984) before statistical analysis. Dried samples were ground to pass through a 1-mm sieve and analyzed for N by dry combustion using a Dumas instrument (Leco TruSpec CHN, Leco Corp., St. Joseph, MI).

Soil samples were collected at weekly intervals from April through June and every other week from July until corn harvest (Fig. 1). Because the initial objective of the killed rye treatment was to quantify only the impact of a killed rye cover crop on corn yield, soil sampling did not begin after killed rye until 2 June 2008. Samples were collected to a depth of 60 cm using a 1.8 cm i.d. soil probe (AMS Inc., American Falls, ID) from the interior rows of each plot. Samples were subdivided into 0 to 30 cm and 30 to 60 cm depths. Four cores were taken per plot and composited by depth. In rye plots, two cores were taken from within the row and two from the interrow. Subsamples were air dried for NO_3–N analysis with the remainder of the sample being dried at 105°C for 24 h for determination of gravimetric soil water content. For NO_3–N analysis, a 15 g portion of ground sample was extracted with 2.0 mol L^{-1} KCl at a 1:2 soil/solution ratio. The extract was then filtered through

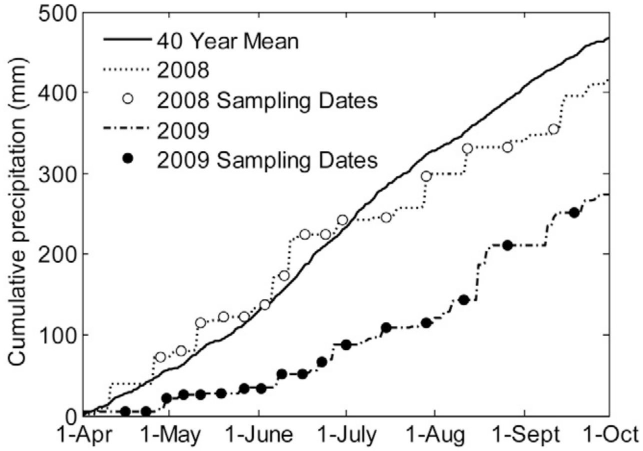

Fig. 1. Cumulative April-September precipitation for 2008 and 2009 and soil sampling dates as well as long-term mean cumulative April-September precipitation (1970–2009) at Morris, MN.

Whatman no. 1 filter paper to obtain a particulate free extract. Samples were analyzed for the sum of NO_2–N and NO_3–N using the colorimetric method (Keeney and Nelson, 1982) and a flow-through injection analyzer (Lachat, Loveland, CO).

Soil cores for bulk density and particle size analysis were collected using a hydraulic soil probe with a core i.d. of 3.8 cm. Six cores were collected in each plot, subsampled by depth, and composited. Samples for bulk density were collected each fall and spring beginning in the fall of 2007 and ending in the fall of 2009. Bulk densities were determined from the total soil mass after drying at 105°C for 24 h. Analysis of variance ($p \leq 0.05$) was used to determine that no difference in bulk density existed between dates. Therefore, a single average bulk density was calculated for each treatment and depth. The obtained bulk density was then used to determine water content as depth of water and NO_3 as kg ha^{-1}. Particle size analysis was performed on samples collected in the fall of 2007 using the method outlined by Gee and Bauder (1986). Particle size data were used to determine water content at field capacity and permanent wilting point at each sampling depth using the method prescribed by Saxton et al. (1986). Water storage at field capacity was 85 mm for the 0 to 30 cm depth and 83 mm for the 30 to 60 cm depth, while water storage at the permanent wilting point was 39 and 36 mm for the 0 to 30 and 30 to 60 cm depths, respectively.

Temperature and precipitation data were collected from a weather station maintained by the University of Minnesota at the WCROC. The weather station was located 0.6 km from the experimental site.

Statistical analyses were performed in Matlab 7.0, 2004 (The MathWorks, Inc., Natick, MA). Data for each year were subjected to two-way ANOVA to determine treatment effect at each sampling date. Block was considered a random effect and treatment a fixed effect. Statistical significance was evaluated at $p \leq 0.05$ unless otherwise noted.

RESULTS AND DISCUSSION

Weather

Average monthly air temperature from September 2007 through August 2009 is given in Table 1. Data are arranged from September through August to represent the rye–corn silage cropping year. Temperatures in September and October were above the 40 yr average in both 2007 and 2008, with departure from average being greater in 2007. Temperatures for the remainder of the growing season were generally below the long-term average in both 2008 and 2009. Annual precipitation was 4% greater than the 40 yr average for the first year of the study but 9% lower for the second year of the study. A detailed representation of spring and summer precipitation and sample collection times is presented in Fig. 1. Cumulative April–September precipitation was near normal for much of the 2008 growing season, but drier than average conditions were experienced in August and September. Cumulative growing season precipitation was below normal for the 2009 growing season, with precipitation being less than average from April through July.

Rye Biomass Yield and Nitrogen Accumulation

Rye biomass yield and aboveground N accumulation were greatest in the first year of the study (Table 2), with the differences likely due to weather. September and October were warmer and wetter in 2007 than 2008, which contributed to more rapid rye establishment and greater growth. Rye seeding rate was higher in 2007, but it is unlikely that the difference was large enough to impact yield (Bishnoi, 1980; Juskiw et al., 2000). Both rye biomass yield and N concentration were generally greater in this study than previously reported in Minnesota (De Bruin et al., 2005; Reicosky and Forcella, 1998; Strock et al., 2004). The greater biomass yield can be attributed to favorable growing conditions, early planting, and high rate of manure application before rye planting in the fall. The high plant N concentration likely also resulted from the high rate of manure application. Because of the additional 3 wk of growth, both rye biomass yield and N uptake were significantly greater in the harvested rye treatment than the killed rye treatment for each year of the study. Allowing additional rye growth in the harvested rye treatment resulted in an increased N accumulation of 104 kg ha^{-1} in 2008 and 80.6 kg ha^{-1} in 2009 compared to killed rye.

Effect of Rye on Soil Moisture

No treatment effect on soil moisture existed between the killed rye and the control treatments at any date for either the 0 to 30 cm or the 30 to 60 cm depth in 2008 (Fig. 2). In the harvested rye treatment, soil moisture was significantly reduced relative to the control in both the 0 to 30 cm and 30 to 60 cm depths at the time of rye harvest on 20 May 2008. The total reduction

Table 1. Average monthly temperature for September 2007–August 2009 and long-term (1970–2009) average monthly temperature for Morris, MN.

Year	Mean monthly temperature, °C												
	Sept.	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Avg.
40-yr mean	13.2	6.9	−1.4	−9.6	−13.1	−9.9	−2.8	6.4	13.8	19.1	20.4	20.1	5.3
2007–2008	16.1	9.7	−0.8	−12.4	−14.5	−13.3	−5.3	4.1	12.0	18.0	21.6	20.1	4.6
2008–2009	15.5	7.6	−0.4	−13.9	−17.3	−11.0	−4.0	5.2	13.1	18.1	18.9	18.4	4.2

in soil water storage to 60 cm at rye harvest was 26 mm (13%). Soil moisture depletion was also observed on 3 June for the 0 to 30 cm depth ($p < 0.07$), but did not exist for the 30 to 60 cm depth. Precipitation totaling 40 mm from 3 June until the next sample collection on 10 June (Fig. 1) returned soil moisture in the harvested rye treatment to that of the control.

In 2009, soil moisture in the killed rye treatment was not reduced at either depth compared with the control treatment (Fig. 3). Soil water storage to 60 cm in the harvested rye treatment was reduced by 28 mm (18%) at the time of rye harvest on 21 May, but this difference was for the 0 to 30 cm depth only. The difference persisted until the 16 June sampling when 15 mm of precipitation returned soil moisture in the harvested rye treatment to near that of the control treatment. A treatment effect was observed in the 30 to 60 cm depth on 9 June. The reason that this reduction was not observed until 3 wk after rye harvest is not clear. Treatment effects were also observed in late July and August with soil moisture after harvested rye being greater than the other treatments. Greater late season soil moisture in the harvested rye treatment indicates reduced water use by corn caused by delayed corn development and lower evapotranspiration. These dynamics observed in the harvested rye treatment, greater soil water depletion in the spring and less depletion in the summer relative to the control, are similar to those reported for corn grown in kura clover living mulch in Wisconsin (Ochsner et al., 2010).

After killed rye, a treatment effect on soil moisture was observed in neither 2008 when spring precipitation was near normal, nor 2009 when spring precipitation was well below average. These results demonstrate that the environmental benefits associated with rye cover cropping, such as N uptake and increased ground cover, can be achieved without negatively impacting water available for the subsequent crop. Conversely, we did not observe a positive impact of soil moisture conservation caused by rye mulch as has been reported by others (Liebl et al., 1992), likely because of insufficient rye biomass or inadequate rainfall.

Results for both 2008 and 2009 indicate that waiting until boot stage to harvest rye for forage comes at the cost of soil moisture depletion. The 27 mm average observed soil moisture depletion in the harvested rye treatment was equivalent to 5% of the typical growing season evapotranspiration (ET) for corn in the region (Suyker and Verma, 2009). For both years, harvesting 1 wk earlier would have eliminated soil moisture depletion induced by the rye, but would have reduced rye yield. These results support the work of Clark et al. (1997) in Maryland who found that killing a winter rye cover crop by early May resulted in no decrease in soil moisture compared to fallow. In Illinois, Liebl et al. (1992) found that a rye cover crop did not deplete soil moisture when killed in late April, but depletion occurred when rye was not killed until early to mid-May. Therefore harvest timing is a method of managing the impact of the rye on subsequent crop yield.

The duration of the soil moisture depletion in the harvested rye treatment was influenced by precipitation. In 2008 when precipitation was near normal, soil moisture depletion persisted for 2 wk following rye harvest, whereas below average precipitation in 2009 resulted in soil moisture depletion persisting for 4 wk after rye harvest. DeBruin et al. (2005) also found that soil moisture following a rye cover crop was dependent on precipitation in Minnesota. In their study, when precipitation was lower than average, a decrease in soil moisture was observed compared with fallow by the time rye was in stem elongation in mid-May, and the difference persisted throughout much of the summer. When precipitation was near normal, no decrease in soil moisture following rye was observed (De Bruin et al., 2005). This suggests allowing rye to reach boot stage before harvest does not negatively impact soil moisture available to the subsequent crop when precipitation is sufficient, but that rye should be harvested earlier if conditions are dry.

Table 2. Rye growth stage, biomass, N concentration, and N content for the killed rye and harvested rye treatments in 2008 and 2009.

Treatment	Sampling date	Growth stage	Rye biomass	N conc.	N content
		Zadoks	kg ha^{-1}	g kg^{-1}	kg ha^{-1}
			2007–2008		
Harvested rye	19 Nov.	25	1046a†	44.2a	46.3a
Killed rye	28 Apr.	25	872a	39.2ab	34.2a
Harvested rye	20 May	38	4102b	33.7b	138b
			2008–2009		
Harvested rye	24 Nov.	23	679a	47.9a	32.5a
Killed rye	30 Apr.	25	680a	27.6b	18.8a
Harvested rye	19 May	39	2504b	39.7c	99.4b

† Numbers within a column and for a given year followed by the same letter are not significantly different at $p \leq 0.05$.

Effect of Rye on Soil Nitrate

Soil NO_3–N on 2 June 2008 was 53 kg ha^{-1} (43%) lower in the 0 to 30 cm depth and 40 kg ha^{-1} (47%) lower in the 30- to 60-cm depth after killed rye compared to the control (Fig. 4). The difference disappeared after 30 June in the 0- to 30-cm depth as N uptake by corn increased. In the 30- to 60-cm depth, the difference persisted through 26 August, presumably because soil N use by corn occurred later in the season in the deeper soil depth. In the harvested rye treatment, sampling in April and May allowed for early season soil NO_3–N use by the rye to be detected. Significant depletion relative to the control was observed from 28 April through 15 July in the 0 to 30 cm depth and from 5 May through 26 August in the 30 to 60 cm depth. The absence of soil NO_3–N depletion in the 30- to 60-cm depth at the time of first

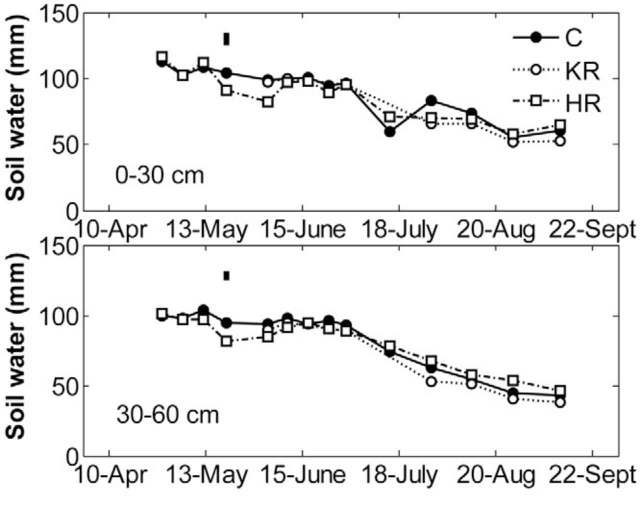

Fig. 2. 2008 soil water (mm) in the 0- to 30-cm and 30- to 60-cm soil depths for the control (C), killed rye (KR), and harvested rye (HR) treatments. Bars representing least significant difference are displayed for dates on which significant differences existed.

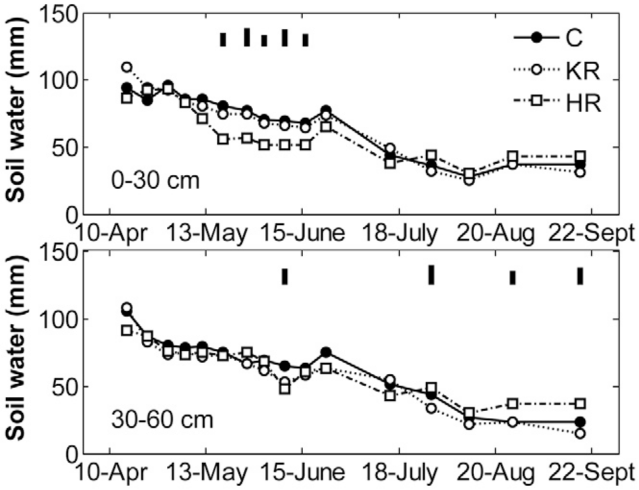

Fig. 3. 2009 soil water (mm) in the 0- to 30-cm and 30- to 60-cm soil depths for the control (C), killed rye (KR), and harvested rye (HR) treatments. Bars representing least significant difference are displayed for dates on which significant differences existed.

sampling suggests that early season rye root development was not as extensive at the deeper depth. By 28 April, soil NO_3–N in the 0 to 30 cm layer was reduced by 90 kg ha^{-1} (74%) in the harvested rye treatment compared to the control, indicating that fall N accumulation by rye can be substantial. Similar soil NO_3–N reduction was likely after killed rye since the rye treatments were identical until the time of rye killing on 25 April. At rye harvest on 19 May, soil NO_3–N after harvested rye was reduced by 114 kg ha^{-1} (93%) in the 0 to 30 cm layer and 46 kg ha^{-1} (68%) in the 30 to 60 cm layer compared to the control. This difference in soil NO_3–N between the harvested rye and the control treatments disappeared only after N use by corn increased. A large reduction in spring soil NO_3–N has also been reported by Stute et al. (2007) in a rye forage-corn silage production system similar to this study. They report a nearly 50% decrease in profile soil NO_3–N after rye compared to winter fallow.

Soil samples collected twelve days after corn planting showed that available soil NO_3–N from 0 to 60 cm was 205, 113, and 40 kg ha^{-1} in the control, killed rye, and harvested rye treatments, respectively. The recommended N fertilizer application for continuous corn production on highly productive land in Minnesota is 135 to 185 kg ha^{-1}, with a credit of 60% of measured spring soil NO_3–N applied toward this recommendation (Rehm et al., 2006). Based on the measured soil NO_3–N levels, additional spring N applications of at least 12, 67, and 111 kg ha^{-1} would have been recommended in the control, killed rye, and harvested rye treatments, respectively. Surprisingly, after manure application in the fall of 2006 and 2007, there was insufficient N to achieve optimum corn yield even in the control treatment. It has been suggested that an additional N credit of 40 kg ha^{-1} per Mg of rye biomass ha^{-1} be given for rye residue (Kessavalou and Walters, 1999). Even with this additional credit, there was insufficient N to achieve optimum yield in the rye treatments.

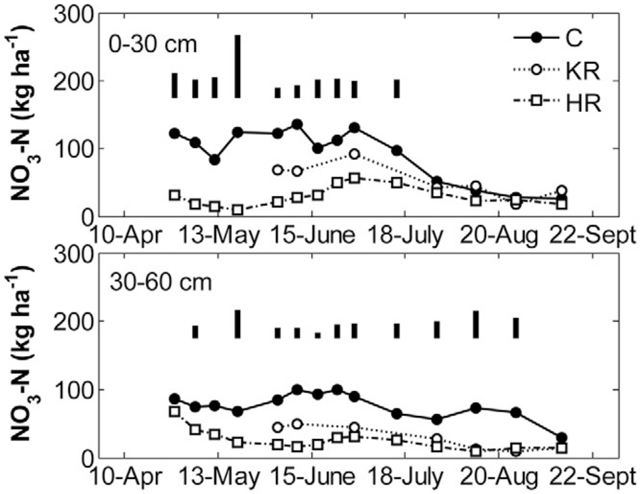

Fig. 4. 2008 soil NO_3–N (kg ha^{-1}) in the 0- to 30-cm and 30- to 60-cm soil depths for the control (C), killed rye (KR), and harvested rye (HR) treatments. Bars representing least significant difference are displayed for dates on which significant differences existed.

The N credit in the rye treatments is given in expectation of N mineralization from rye residue during the corn growing season. Mineralization from rye biomass is likely part of the cause for the increase in soil NO_3–N concentration in the 0- to 30-cm depth which occurred in May and June of 2008 in both the killed rye and harvested rye treatments. After killed rye, an increase in soil NO_3–N of 24 kg ha^{-1} occurred between 10 and 30 June. After harvested rye, an increase in soil NO_3–N of 42 kg ha^{-1} in the 0- to 30-cm depth was observed between 20 May and 30 June. Wagger (1989) reported that by 12 wk after killing, 42% of N retained in a rye cover crop was released, with little additional N becoming available thereafter. Thus it is reasonable to infer that a portion of the observed increase in soil NO_3–N was due to mineralization of the rye, with N mineralization from manure and soil organic matter also contributing to the observed increase.

In 2009, soil NO_3–N depletion in the rye treatments was not as great as the previous year. Soil NO_3–N depletion after killed rye was observed only well after rye had been killed (Fig. 5). Compared with the control, soil NO_3–N depletion after killed rye was observed on May 27 in the 0- to 30-cm depth and on 15 and 29 July in the 30- to 60-cm depth. The late occurrence of the treatment effect could have resulted from different rates of N mineralization and N uptake by corn in the killed rye treatment compared to the control. In the harvested rye treatment, soil NO_3–N depletion was observed at the time of rye harvest and for most sampling dates through 23 June for the 0- to 30-cm depth. For the 30 to 60 depth, soil NO_3–N depletion was observed beginning 9 June and for most sampling dates through 29 July. The greater soil NO_3–N depletion after harvested rye results from an additional 3 wk of rye growth. By the time of rye harvest on 21 May, soil NO_3–N after harvested rye had been depleted by 41 kg ha^{-1} (45%) in the 0- to 30-cm depth and 42 kg ha^{-1} (42%) in the 30- to 60-cm depth.

Unlike the previous year, no early season soil NO_3–N depletion was observed in the harvested rye treatment in 2009, possibly resulting from reduced N accumulation in rye biomass. By late April, N accumulation was lower in 2009 (19 kg ha^{-1}) than 2008 (34 kg ha^{-1}). Another explanation is the much lower soil NO_3–N in the 0- to 30-cm layer in the control treatment in 2009, which indicates reduced mineralization compared with the previous year or leaching of N out of the 0- to 30-cm layer. The latter explanation is supported by the higher precipitation during the winter of 2008–2009, relative to the previous year. Variability in measured soil NO_3–N was greater in 2009 making treatment effects more difficult to detect.

Twelve days after corn planting, available soil NO_3–N from 0 to 60 cm was 241, 179, and 149 kg ha^{-1} in the control, killed rye, and harvested rye treatments, respectively. Based on these measured soil NO_3–N levels, spring fertilizer N applications would have been recommended after killed rye (28 kg ha^{-1}) and harvested rye (46 kg ha^{-1}), but there was sufficient N in the control treatment to achieve optimum corn yield in Minnesota (Rehm et al., 2006). Assuming an additional N credit of 40 kg ha^{-1} per Mg of rye biomass ha^{-1} in the rye treatments, there was sufficient N to achieve optimum corn yield after killed rye, but not after harvested rye.

In 2009, an increase in soil NO_3–N concentration of greater than 100 kg ha^{-1} was observed in all treatments from 19 May through 1 July in the 0- to 30-cm depth. Because this mineralization occurred in both the control and rye treatments, the increase in soil NO_3–N was not due solely to break down of rye residue but also resulted from N mineralization from manure and soil organic matter. Additionally, available profile soil NO_3–N was greater on 1 July 2009, after mineralization, than for the same time in 2008. This suggests a buildup of soil N from multiple high rate applications of manure. Research suggests that approximately 50% of total N in injected liquid dairy manure is available the first year after application, with an additional 25% being available the second year (Russelle et al., 2008). Mineralization of manure N from each of three manure applications likely resulted in the large increase in soil NO_3–N observed in all treatments in 2009. This has been previously observed in a continuous corn production system in Wisconsin, where Munoz et al. (2003) found that applying three consecutive years of dairy manure at a rate of about 180 kg ha^{-1} available N resulted in increasing spring and fall soil NO_3–N levels over time.

Soil NO_3–N concentration was reduced after killed rye in each year of the study, but in only the first year was soil NO_3–N depletion great enough to prevent optimum corn production. The decrease was not as large the second year. This, coupled with greater end of season soil NO_3–N in 2009 than 2008 for all treatments, suggests a buildup of soil NO_3–N. Winter rye cover cropping does not alleviate the buildup of total soil N as the N is recycled between plants and soil. However, a winter rye cover crop can immobilize soil NO_3–N in the fall and spring when leaching potential is greatest. Subsequent breakdown of rye residue releases N during the corn growing season.

As with killed rye, soil NO_3–N was reduced after harvested rye each year of the study. The reduction was greater after harvested rye as an additional 3 to 4 wk of rye growth resulted in greater N uptake. Soil NO_3–N depletion was large enough to suppress subsequent corn yield based on University of Minnesota recommendations for fertilizing corn. Soil NO_3–N depletion after harvested rye was not as dramatic the second year of the study, presumably because of lower rye biomass yield in 2009 and buildup of soil NO_3–N. The N scavenging ability of rye was observed in both the killed rye cover crop and harvested rye forage crop. Killing the winter rye is preferable when rye is not needed as forage or when possible yield reduction in the following corn crop cannot be tolerated, while harvesting the rye is preferable when the rye can be used as forage. Harvesting rye reduces buildup of soil N as N retained in rye biomass is removed from the field rather than recycled as in the case of the killed rye cover crop.

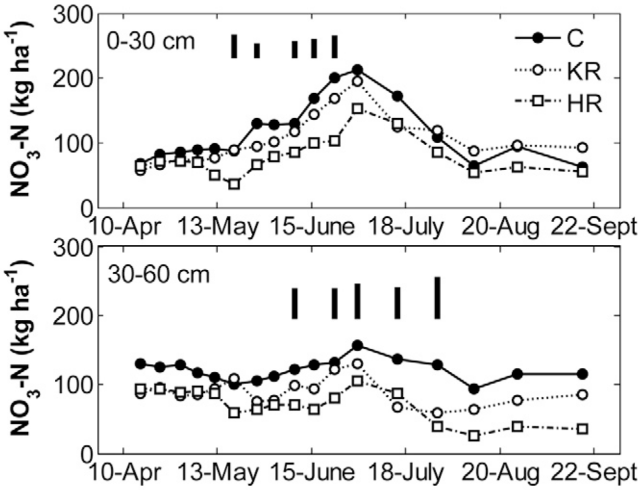

Fig. 5. 2009 soil NO_3–N (kg ha^{-1}) in the 0- to 30-cm and 30- to 60-cm soil depths for the control (C), killed rye (KR), and harvested rye (HR) treatments. Bars representing least significant difference are displayed for dates on which significant differences existed.

Corn Development and Yield following Rye Cover Crop

Early season corn height after killed rye was similar to corn in the control treatment in both 2008 and 2009 (Fig. 6). Mid-season corn height was reduced compared to the control, but the difference disappeared by the time of harvest. After harvested rye, a reduction in corn height compared to the control was observed for most sampling dates in 2008 and 2009 (Fig. 6). The mid-season difference was greater in 2009 when conditions were drier. Reduced corn height was observed at harvest in 2008, but not in 2009. Treatment effects on corn growth stage showed similar trends as those for height (data not shown).

The greater delay in early corn development after harvested rye resulted in part because of greater reduction in soil moisture. Reduced soil temperature and increased allelopathic effects may have also resulted in slower corn development in the harvested rye treatment, but these factors were not measured. Raimbault et al. (1991) found that corn seeded immediately after killing rye

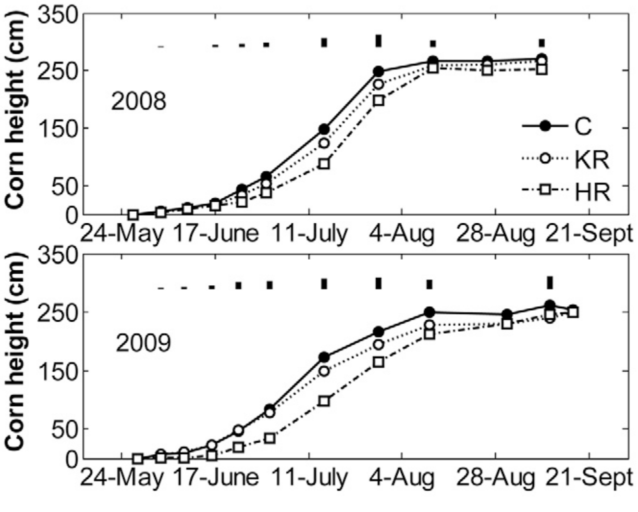

Fig. 6. Corn height (cm) for the control (C), killed rye (KR), and harvested rye (HR) treatments in 2008 and 2009. Error bars representing least significant difference are displayed for dates on which significant differences existed.

Table 3. Corn whole plant moisture, silage biomass yield, N concentration, and N content for the control, killed rye, and harvested rye treatments in 2008 and 2009.

Treatment	Moisture	Biomass Yield	N conc.	N content
	%	Mg ha^{-1}	g kg^{-1}	kg ha^{-1}
		2008		
Control	66.4a†	17.7a	12.0a	213a
Killed rye	66.5a	16.9a	11.9a	202a
Harvested rye	69.6b	13.7b	11.3a	154b
		2009		
Control	61.5a	22.7a	12.2a	277a
Killed rye	62.8a	22.2a	12.3a	272a
Harvested rye	67.7b	17.7b	12.8a	227a

† Numbers within a column and for a given year followed by the same letter are not significantly different at $p \leq 0.05$.

resulted in lower corn yield than corn seeded after rye that had been killed 2 wk earlier. They attributed the lower yield after late killed rye to increased rye residue, reduced soil moisture, and greater allelopathic effects. The increased residue decreases soil temperature thereby slowing early corn development (Burrows and Larson, 1962; van Wijk et al., 1959). Decreased soil temperature induced by residue occurs even when surface cover is vertically oriented (Bristow, 1988) as with standing rye stubble in this study. No-till corn planting in the rye treatments likely also resulted in cooler soil temperatures. In Michigan, Kravchenko and Thelen (2007) attributed delayed emergence, longer time to tasseling, and reduced corn height in corn no-till seeded into winter wheat residue to reduced soil temperature and plant available N.

At corn harvest, no differences in whole plant yield, moisture, N concentration, and N uptake existed between the killed rye and the control for either year of the study (Table 3.) Whole plant corn moisture indicates the maturity of corn at harvest was the same in these treatments. The similar corn yields observed here corroborate the work of Singer et al. (2008) in Iowa who reported that a winter rye cover crop after fall manure application had no impact on corn grain yield when killed in mid-April. After harvested rye, corn silage yield was reduced by 4.0 Mg ha^{-1} (23%) in 2008 and 5.0 Mg ha^{-1} (22%) in 2009 compared to the control. Corn N content was reduced in 2008. Suppressed corn yield in the harvested rye treatment was likely due to delayed development and insufficient soil NO_3–N in 2008. Previous work in Minnesota has shown a more than 30% decrease in corn biomass yield when soil NO_3–N was decreased from 193 to 53 kg ha^{-1} (Jokela and Randall, 1989). Reduced soil moisture and the presence of rye residue impaired early corn development, and maturity at harvest was reduced. In 2009, suppressed corn yield in the harvested rye treatment likely resulted from delayed early season development induced by rye residue and the prolonged period of soil moisture depletion after rye was harvested. Soil NO_3–N was reduced after harvested rye in 2009, which may have also contributed to the decreased corn yield.

Table 4. Total biomass yield, total N sequestered in corn and rye biomass, and total harvested N, for the control, killed rye, and harvested rye treatments in 2008 and 2009.

Treatment	Biomass yield	Sequestered N	Harvested N
	Mg ha^{-1}	–kg ha^{-1}–	
		2008	
Control	17.7a†	213a	213a
Killed rye	16.9a	236ab	202a
Harvested rye	17.8a	292b	292b
		2009	
Control	22.7a	277a	277a
Killed rye	22.2a	291a	272a
Harvested rye	20.2a	327a	327a

† Numbers within a column and for a given year followed by the same letter are not significantly different at $p \leq 0.05$.

Corn yield was greater in 2009 than 2008 because of timely precipitation and more advanced corn maturity at harvest in 2009. While total precipitation was greater in 2008, precipitation at and around the time of corn silking was greater in 2009. Silking has previously been demonstrated to be a critical time for corn growth, with the potential for decreased yield due to inadequate moisture being greatest during this development period (Denmead and Shaw, 1960). Additionally, the later harvest in 2009 likely resulted in more advanced corn maturity at harvest and increased corn yield.

Double cropped corn yield after winter rye has previously been shown to be reduced compared to corn after fallow when N is not limiting. In a double crop system in Ontario, Canada, Raimbault et al. (1990) found no-till corn silage yield was reduced by 27% after a harvested winter rye cover crop compared to conventional till corn silage. Similarly, Tollenaar et al. (1992) found no-till corn silage yield after a harvested winter rye cover crop was reduced by 17% compared to roto-till corn silage after winter fallow in Ontario, Canada. The reduced corn yield observed after harvested rye in this study corresponds well with previous work where corn was double cropped with rye.

One appeal of double cropping corn silage with rye is the potential to increase total biomass production while also realizing the environmental benefits of fall seeded winter rye. In this study, biomass production for corn after winter fallow compared to combined biomass of rye and corn in the harvested rye treatment was similar for each year of the study (Table 4). The amount of N sequestered in rye biomass and removed in harvested forage was greatest in the harvested rye treatment in 2008, but no differences existed in 2009. The inability to increase forage yield in the double crop system used in this study indicates that this system is unlikely to be adopted in Minnesota unless the economic value of rye forage exceeds that of corn silage. Alternative management strategies such as earlier rye harvest to conserve soil moisture and NO_3–N, tillage before corn planting to minimize the impact of rye residue on soil temperature, and additional spring fertilization may help reduce the impact of the rye on subsequent corn yield. Conversely, this study demonstrates that the environmental benefits of winter cover cropping can be achieved without negatively impacting subsequent corn yield if rye is terminated early. Killing the rye several weeks before corn planting conserves soil moisture and prevents excessive N uptake by the rye, while the limited rye residue has less impact on early season corn development. However, in this system N is recycled between the plant and soil, and is not removed in rye biomass, resulting in long-term build up of soil nutrients if they are applied in excess.

CONCLUSION

A winter rye cover crop can be fall seeded to mitigate some of the environmental concerns associated with corn silage production. Rye can be managed as a cover crop by chemical termination or harvested as part of a rye–corn silage double-crop forage production system. Producers may regain some of the cost of cover cropping by harvesting the rye as forage. However, resource depletion induced by rye can result in yield suppression of the primary crop.

The focus of this research was to quantify soil moisture and soil NO_3–N depletion induced by killed vs. harvested rye and to monitor effects on subsequent corn development and yield. Soil moisture was not depleted after killed rye, but an additional 3 to 4 wk of growth in the harvested rye treatment resulted in soil moisture depletion. Depletion persisted longer when precipitation was below the long-term average than when precipitation was near normal. The soil moisture depletion in the double crop system could be alleviated where irrigation is possible or in areas with longer growing seasons allowing corn planting after rye to be delayed until soil moisture is replenished through precipitation. Soil NO_3–N was decreased after a killed winter rye cover crop, but the observed decrease was large enough to affect corn yield only in 2008. The period of additional rye growth in the harvested rye treatment resulted in greater depletion of soil NO_3–N than after killed rye. The difference was likely large enough to reduce corn yield in both 2008 and 2009. Depletion of soil NO_3–N in the harvested rye system could be overcome by additional N fertilization in the spring. Annual manure applications in this study resulted in buildup of soil NO_3–N. Build up was not as great in the harvested rye because more N was removed in forage than in the killed rye treatment. In general, the effect of the killed rye cover crop on corn development was small. Corn after killed rye yielded similarly to corn in the control treatment each year of the study. Corn development was delayed in the harvested rye treatment, and corn yield was reduced. Total biomass production was similar for all treatments.

Allowing rye to grow until boot stage resulted in greater resource depletion, which negatively impacted subsequent corn. Later management in the harvested rye treatment also resulted in increased rye residue and possibly greater allelopathic effects, which contributed to delayed corn development. Environmental benefits associated with winter rye cover cropping were achieved in both the killed and harvested rye treatments. Corn yield reduction after harvested rye makes this management strategy impractical in the U.S. Upper Midwest unless measures to address soil resource depletion are taken or the economic value of the rye forage is higher than that of corn silage. The possibility of reduced corn yield after harvested rye may be acceptable for large livestock facilities which have surplus N. The double crop system supports a higher N application rate near the source and can reduce manure transportation costs. The inclusion of rye in a corn silage production system is feasible in the U.S. Upper Midwest, but the system must be carefully managed to avoid impacting subsequent corn yield.

ACKNOWLEDGMENTS

Funding for this work was provided by USDA-ARS and the Oklahoma Agricultural Experiment Station.

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