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Rye Cover Crop Management for Corn Production in the Northern Mid-Atlantic Region

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ABSTRACT

A late-killed rye (*Secale cereale* L.) cover crop has many environmental benefits. However, rye can reduce following corn (*Zea mays* L.) yield and compromise pre-emergence herbicide activity. Our hypotheses were (i) rye reduces corn yields, especially if killed at late-boot stage; (ii) in-row tillage helps alleviate yield reductions; and (iii) postemergence weed control will be more effective than pre-emergence weed control in the presence of rye mulch. Corn was planted 7 to 10 d after rye was killed at early- and late-boot stage with no-till or zone-till. A no-rye control was included for comparison. Herbicide programs included half rate of pre-emergence herbicide, full rate of pre-emergence herbicide, and a postemergence herbicide. Rye biomass, soil bulk density, corn yield and population, and weed biomass were determined. Average rye biomass was 1400 kg ha^{-1} dry matter (DM) at early-boot stage and 4200 kg ha^{-1} DM at late-boot stage. In 2001, bulk density was reduced 0.08 Mg m^{-3} in the 0- to10-cm depth in the late-killed rye plots compared with no rye or early killed rye. Rye never reduced no-till corn yields. Allelopathic effects of rye on corn were absent, calling for a better understanding of its underlying principles. Zone-till did not improve corn yields. Good weed control resulted from all herbicide programs due to low weed severity. The results suggest that rye cover crops will not reduce corn yields if rye is killed 7 to 10 d before corn planting and if adequate N is applied.

Rye is a common cover crop in the northeastern USA because it can be established in late fall and is able to withstand cold winter temperatures (Duiker and Curran, 2003). A rye cover crop can (i) reduce erosion, especially after low-residue crops such as soybean [*Glycine max* (L.) Merr.] and corn silage; (ii) protect nitrate from leaching (Brandi-Dohrn et al., 1997; Kessavalou and Walters, 1997); (iii) contribute to soil organic matter and aggregation (Tisdall and Oades, 1982; Oades, 1984); (iv) conserve water by providing a mulch after it is killed (Steiner, 1994); and (v) control weeds (Reddy, 2003). Because of its multiple benefits, many producers are using rye as a cover crop, and environmental organizations are actively promoting it to protect water quality.

Although rye is a well-known cover crop, there are still many questions regarding its management. As a cover crop in Pennsylvania, rye is planted in the fall and killed before planting corn. To capture the environmental benefits of rye without reducing corn yields requires balancing potential yield losses from delaying the corn planting date with the accumulation of rye biomass by delaying its kill date. Yield reductions due to delayed corn planting are well established (Roth and Beegle, 2003). In addition, a late-killed rye cover crop can deplete surface moisture, increasing drought risk for the corn crop (Ebelhar et al., 1984; Raimbault et al., 1991). Also, allelopathic compounds released by rye may reduce corn yield (Raimbault et al., 1990; Kessavalou and Walters, 1997). However, a late-killed rye cover crop may also have positive effects on the following corn crop, such as summer water savings under a dead mulch and soil improvement because of the decaying root system. In a Maryland study, benefits apparently compensated for drawbacks because a late-killed rye cover crop, resulting in delayed corn planting, was not detrimental to corn yield (Clark et al., 1997a, 1997b).

A number of precautions can be taken to reduce the potential risks of a rye cover crop on the following corn crop. Killing the rye cover crop at planting is likely to result in stand and crop yield reductions (Eckert, 1988), but killing the rye 1 to 2 wk before planting reduces the risk of soil water depletion and allelopathic effects (Ewing et al., 1991). In some cases, however, allelopathic effects and depressed corn yields have been reported even when a young rye cover crop was killed 1 wk before corn planting (Kessavalou and Walters, 1997). In-row cultivation may be an option to minimize the phytotoxic effect of rye on corn (Raimbault et al., 1991).

Weed control in no-till crop production generally relies on the use of herbicides. A rye cover crop can help control weeds and may allow for reduced herbicide use after rye has been killed with a burn-down herbicide. A winter rye cover crop can impact weeds in several ways. Rye competes with weeds before it is killed and after that provides a mulch that physically and chemically suppresses weeds in the primary crop (Teasdale and Mohler, 1993). The rye mulch will reduce light penetration to the soil surface and lower soil temperatures, slowing weed seed germination and early growth. Allelopathic properties of rye may suppress weeds (Putnam and DeFrank, 1983; Shilling et al., 1985). These observations suggest that a postemergence, foliar-applied herbicide program in corn planted into a heavy rye cover crop may offer acceptable weed control. However, insufficient weed control as well as increased weed problems with a rye cover crop have also been reported (Masiunas et al., 1995; Koger et al., 2002; Reddy, 2003). The effectiveness of pre-emergence herbicides that need to make contact with the soil may be compromised by rye mulch because they are absorbed by rye residue (Banks and Robinson, 1982) or cannot be sprayed uniformly (Erbach and Lovely, 1975).

The objectives of this study were to evaluate (i) effects of timely versus delayed planting of corn into a rye cover crop, with the expectation that corn yield would be re-

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Abbreviations: DM, dry matter; NT-R, no-till corn without a rye cover crop; NT+R, no-till corn into a rye cover crop; ZT+R, zone-till corn into a rye cover crop.

duced due to delayed planting into rye mulch; (ii) benefits of in-row tillage with small and large amounts of rye mulch, expecting the in-row tillage to improve yields; and (iii) effectiveness of pre- and postemergence herbicide programs with and without rye mulch, expecting the postemergence program to be more effective.

MATERIALS AND METHODS

The experiment was conducted from 2001 to 2003 on the Russell E. Larson Agricultural Research Center in Rock Springs, Centre County, PA (40°44′ N, 77°57′ W). Different fields were used each year in close proximity to each other. The soil was a Hagerstown silt loam (fine, mixed, semiactive, mesic Typic Hapludalf) in 2001 and 2002 and a Murrill channery silt loam (fine-loamy, mixed, semiactive, mesic Typic Hapludult) in 2003. The previous crop was spring oat (*Avena sativa* L.) in all years. The oat grain and the straw were removed before rye cover crop establishment.

Rye was no-till seeded at 126 kg ha^{-1} in the fall (23 Oct. 2000, 3 Oct. 2001, and 25 Sept. 2002). Ammonium sulfate was broadcast-applied in March each year at 71 kg ha^{-1} N to stimulate rye growth. The experiment was a split-split plot design with four replicates. Two corn planting/rye kill dates (early and late) were the main plot, three rye management treatments were the subplots, and three herbicide programs sub-subplots. Sub-subplots were 4.6 m wide by 9.1 m long. The three rye treatments were no-till corn without a rye cover crop (NT-R), no-till corn into a rye cover crop (NT+R), and zone-till corn into a rye cover crop (ZT+R). Rye was killed with 1.12 kg a.i. ha^{-1} glyphosate [*N*-(phosphonomethyl)glycine] at all control dates. The rye in the NT-R treatment was killed in late fall or early spring, resulting in little or no rye residue being left at planting. The early and late kill dates for rye in the NT+R and ZT+R treatments were early boot (1 May 2001, 23 Apr. 2002, and 25 Apr. 2003) and late boot (11 May 2001, 8 May 2002, and 14 May 2003). Corn was planted between 7 and 10 d after the rye was sprayed. Early and late planting dates for corn were therefore 9 and 22 May 2001, 1 and 11 May 2002, and 2 and 22 May 2003. Corn hybrid Agway 5206 (produced by Growmark FS, Inc., Bloomington, IL) was planted in 2001 and 2002 and Pioneer 34H31 (produced by Pioneer Hi-Bred International, Inc., Des Moines, IA) in 2003. Both are full-season hybrids recommended for use in central Pennsylvania (102 and 109 relative maturity ratings, respectively). Corn was planted with a six-row John Deere planter (Model 1780 Max Emerge Plus, Deere and Co., Moline, IL) on 76-cm row spacing at a seeding rate of 70 000 seeds ha^{-1}. The planter was equipped with starter fertilizer injection coulters, bubble coulters to cut residue and soil, double-disk seed slot openers, seed firmers to press the seed firmly into the opened seed slot, and two rubber closing wheels to close the seed slot. Tefluthrin soil insecticide [2,3,5,6-tetrafluoro-4-methylbenzyl (*Z*)-(1*RS*,3*RS*)-3-(2-chloro-3,3,3-trifluoroprop-1-enyl)-2,2-dimethylcyclopropanecarboxylate] was applied with the corn seed at planting at a rate of 0.12 kg a.i. ha^{-1}. Based on Penn State fertilizer recommendations, 180 kg ha^{-1} urea N was broadcast before planting corn, and 275 kg ha^{-1} 10–20–10 starter fertilizer was injected 5 cm beside and 5 cm below the seed at planting.

Zone tillage was performed with a Rawson Zone Tillage system (Unverferth Manufacturing Co. Inc., Kalida, OH), which consists of three 41-cm-diam., 13-wave fluted coulters that till a 15-cm-wide by 10-cm-deep zone in which corn is planted. In 2001, the zone-till coulters were mounted on the frame of the no-till planter. In 2002 and 2003, zone-till was performed immediately before planting with a zone-till cart.

The three herbicide treatments were half rate of pre-emergence herbicide applied at planting (PREHALF), full rate of pre-emergence herbicide (PREFULL), and full rate of post-emergence herbicide (POST). Herbicide applications for the PREFULL program were 1.68 kg a.i. ha^{-1} atrazine [6-chloro-*N*-ethyl-*N*′-(1-methylethyl)-1,3,5-triazine-2,4-diamine] plus 0.078 kg a.i. ha^{-1} isoxaflutole {(5-cyclopropyl-4-isoxazolyl)[2-(methylsulfonyl)-4-(trifluoromethyl)=phenyl]methanone} in 2001 and 2002. In 2003, 1.61 kg a.i. ha^{-1} s-metolachlor [2-chloro-*N*-(2-ethyl-6-methylphenyl)-*N*-(2-methoxy-1-methylethyl)acetamide] was added to this mixture for improved yellow nutsedge (*Cyperus esculentus* L.) control. Half these rates were applied in the PREHALF program. The PRE herbicides were applied immediately after corn planting. The POST program was applied to V3 corn about 5 wk after corn planting and included 0.013 kg a.i. ha^{-1} rimisulfuron {*N*-[[(4,6-dimethoxy-2-pyrimidinyl)amino]carbonyl]-3-(ethylsulfonyl)-2-pyridinesulfonamide}, 0.013 kg a.i. ha^{-1} nicosulfuron {2-[[[[(4,6-dimethoxy-2-pyrimidinyl)amino]carbonyl]amino]sulfonyl]-*N*,*N*-dimethyl-3-pyridinecarboxamide}, 0.84 kg a.i. ha^{-1} atrazine, and 0.140 kg a.i. ha^{-1} dicamba (3,6-dichloro-2-methoxybenzoic acid). A nonionic surfactant was included at 0.25% v/v with the POST program along with 28% urea ammonium nitrate at 2% v/v. Both the PRE and POST herbicide mixtures target a wide spectrum of annual grass and broadleaf weeds and are commonly used in Pennsylvania. All herbicides were applied using a CO_2–pressurized backpack sprayer equipped with AI11002VS flat-fan nozzles calibrated to deliver 187 L ha^{-1} at 345 kPa.

Aboveground rye DM production was measured by harvesting five to eight 0.5-m^2 quadrants from the areas between the replicates at the rye kill dates. The rye samples were weighed after being dried at 70°C for 24 h or longer until completely dry. Soil bulk density and water content in the top 0 to 20 cm was measured 8 wk after planting of NT-R and NT+R treatments with a moisture/density gauge (model 3411B, Troxler Int., Research Park, NC) in 2001. Three moisture/density measurements were taken between the rows in the center of each plot. Corn stand was evaluated at about 10 wk after planting by counting all plants in the center two rows of each plot. Aboveground weed biomass was collected from two 1.1-m^2 areas per plot about 12 wk after planting. Weed dry weight was determined as previously described for rye biomass. Corn yield (expressed at 15.5% moisture content) was determined by harvesting the three center rows of each plot with a small-plot combine. Corn yield and population were analyzed with PROC MIXED in SAS (SAS Inst., 2001) using rep(year), rep × planting(year) and rep × planting × tillage(year) as random effects. Separation of means was determined with the LSMEANS statement. Yield effects, being normally distributed, were analyzed without transformation. Plant populations were exponentially transformed [exp(population/11 700)] before statistical analysis to obtain a normal distribution. Weed control data were not normally distributed and were analyzed using Friedman's nonparametric test for the two-way lay-out using PROC FREQ in SAS (Hollander and Wolfe, 1999). Weed control was not influenced by ZT+R, so only the effects of NT-R vs. NT+R, planting date, and herbicide treatment on weed control were compared. If significant treatment effects were detected, Friedman's two-way nonparametric ANOVA was calculated and LSD used to separate means (http://ftp.sas.com/techsup/download/sample/samp_lib/statsampTwoWay_Nonparametric_Anova.html; verified 19 May 2005).

Table 1. Rye dry matter production at early† and late‡ corn planting dates.§

Corn planting date	2001	2002	2003
	kg ha^{-1}		
Early	1143 ± 400	no data¶	1568 ± 503
Late	1833 ± 722	3740 ± 311	7075 ± 681

† 9 May 2001, 1 May 2002, and 2 May 2003.
‡ 22 May 2001, 11 May 2002, and 22 May 2003.
§ Mean ± standard deviation.
¶ Excluded because of inconsistencies.

RESULTS

Rye Biomass Accumulations

Lowest rye biomass accumulation was in 2001, and the highest biomass accumulation occurred in 2003 (Table 1). Average monthly temperatures are not the likely explanation for differences in rye growth (Fig. 1). Instead, low rye biomass accumulation in 2001 may be attributed to a late planting date (end of October of 2000) and low precipitation in January, February, and March (Fig. 2). In contrast, rye was planted at the beginning of October and the end of September of 2001 and 2002, respectively. In addition, the glyphosate application was delayed 1 week beyond late-boot stage of rye in 2003 because of extremely wet field conditions. On average, 1400 kg ha^{-1} biomass accumulated at early-boot stage and 4200 kg ha^{-1} at late-boot stage. These biomass accumulations are similar to those reported by Clark et al. (1997a).

Bulk Density Effects

Bulk densities measured in 2001 in the 0- to 10-cm depth were lower in the late-planted NT+R treatment than in the other tillage by planting combinations (Table 2). We propose that the key to bulk density reduction is the root biomass production of the rye, which should be directly related to aboveground biomass. As was earlier pointed out, rye biomass accumulation was less in 2001 than in the other 2 yr, probably the result of late rye establishment in the fall of 2000. It seems, therefore, that rye killed in early-boot stage may also have a bulk density reducing effect as long as it is established early in the fall (before 1 October in our area). Raper et al. (2000) reported a reduction in penetration resistance due to rye mulch but no reduction in bulk density.

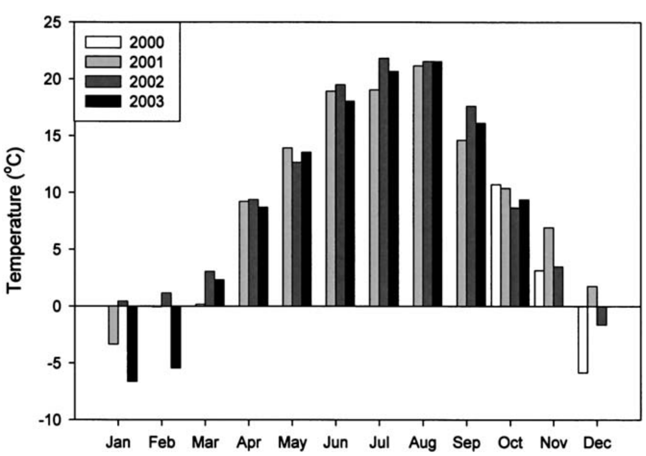

Fig. 1. Average monthly temperatures at the research station during experimental period.

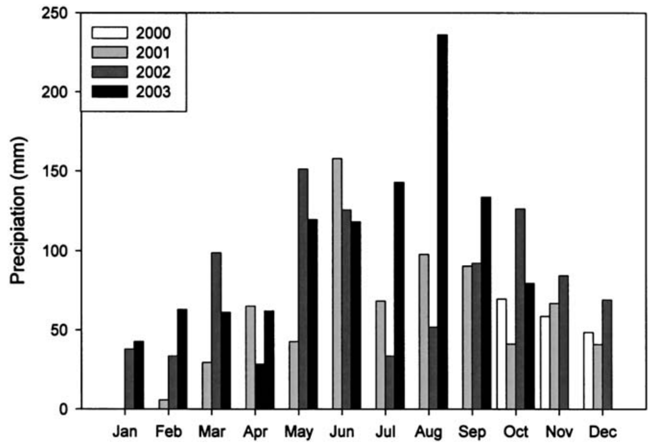

Fig. 2. Total monthly precipitation at the research station during experimental period.

Corn Population

Planting date and rye management did but herbicide treatments did not affect corn plant populations (Table 3). Late planting resulted in lower populations (Table 4). The greatest reduction in plant population with late planting was in the ZT+R treatment, but even in NT-R (p = 0.21) and NT+R (p = 0.28), there was a trend toward reduction in plant population due to late planting. In general, ZT+R had the lowest, NT-R the highest, and NT+R intermediary plant populations.

Low average plant populations with ZT+R were the result of the poor performance of ZT+R in 2001. In the other years, ZT+R did not show population reductions compared with NT+R. Low plant populations in ZT+R in 2001 can be attributed to the zone-till coulters (mounted on the planter) not penetrating the dry soil. This effect was exacerbated in late-killed rye. It was evident that planter weight should have been increased to guarantee coulter penetration. To minimize problems in 2002 and 2003, zone-till was performed immediately before planting with a zone-till cart. A filled 2700-L tank on the zone-till cart guaranteed sufficient coulter down pressure. However, in 2002 and 2003, ZT did not improve corn plant populations over NT as had been expected. This was probably because ZT coulters did not penetrate the rye mulch and root mass enough, even when high down pressure was exerted on the coulters.

Table 2. Corn planting date and rye management† effects on dry bulk density (2001).

Corn planting date	NT-R	NT+R
	Mg m^{-3}	
	0–10 cm depth	
Early	1.48a‡	1.48a
Late	1.48a	1.40b
	10–20 cm depth	
Early	1.58ab	1.58ab
Late	1.59a	1.53b

† NT-R = no-till without rye; NT+R = no-till with rye.
‡ Values within depths followed by the same letter are not statistically different at $p \leq 0.05$.

Table 3. Significance of treatment effects on corn population and yield.

Source of variation	df	Populations ($p > F$)	Yield ($p > F$)
Year	2	0.3402	0.0012
Planting date	1	0.0107	0.0753
Year × planting date	2	0.6334	0.3336
Rye	2	<0.0001	0.0019
Year × rye	4	<0.0001	0.0003
Planting date × rye	2	0.1914	0.0899
Year × planting date × rye	4	0.0132	0.0285
Herbicide	2	0.1064	0.4888
Year × herbicide	4	0.0153	0.1201
Planting date × herbicide	2	0.5524	0.4695
Rye × herbicide	4	0.7259	0.7927
Planting date × rye × herbicide	4	0.3734	0.2734
Year × planting date × herbicide	4	0.9014	0.1337
Year × rye × herbicide	8	0.0886	0.9634
Year × planting date × rye × herbicide	8	0.1794	0.1592

Except for ZT+R, planting date did not affect populations in 2001. In 2002, however, plant populations in NT-R were reduced in late-planted compared with early planted corn. In NT+R, plant populations were no different between early and late planting. Crusting of bare soil by heavy precipitation following the second planting date may be responsible for these results. The rye mulch protected the soil against the impact of raindrops in the late-planted NT+R. In 2003, plant populations were reduced in the late-planted compared with early planted NT+R. Reduced corn populations in the late-planted NT+R were attributed to corn being planted in wet soil, which resulted in "hairpinning." Rye residue was pushed down below the seed, and the seed slot was not closed properly. Slug activity was observed in the open seed slot below the thick rye mat. Zone-till eliminated the plant population reduction due to late planting but did not improve it over NT+R. If rye was killed early, the negative effects of wet soil conditions at planting were limited.

Table 4. Corn planting date and rye management† effects on corn populations.

	NT-R	NT+R	ZT+R	*Average*
		plants ha^{-1}		
		2001		
Early	63 800a‡	64 000a	48 300b	*58 700Y§*
Late	66 500a	62 700a	29 600c	*52 900X*
Average	*65 100A¶*	*63 400A*	*38 900B*	*55 800#*
		2002		
Early	61 500b	53 600c	59 200bc	*58 100X*
Late	53 000c	56 300bc	56 300bc	*55 200X*
Average	*57 300A*	*54 900A*	*57 700A*	*56 600*
		2003		
Early	60 900a	57 900ab	58 900ab	*59 300Y*
Late	57 700ab	48 900c	52 700bc	*53 100X*
Average	*59 300A*	*53 400B*	*55 800AB*	*56 200*
		2001–2003		
Early	62 100a	58 500ab	55 500b	*58 700Y*
Late	59 100ab	56 000ab	46 200c	*53 800X*
Average	*60 600A*	*57 200B*	*50 800C*	*56 200*

† NT-R = no-till without rye; NT+R = no-till with rye; ZT+R = zone-till with rye.
‡ Planting date × rye management values within years followed by same lowercase a, b, or c are not significantly different at $p \leq 0.05$.
§ Average populations per planting date within years followed by same uppercase X or Y are not significantly different at $p \leq 0.05$.
¶ Average populations for rye management within years followed by same uppercase A, B, or C are not significantly different at $p \leq 0.05$.
# Average plant populations were not statistically different between years at $p \leq 0.05$.

Table 5. Corn planting date and rye management† effects on corn yields.

Corn planting date	NT-R	NT+R	ZT+R	*Average*
		Mg ha^{-1}		
		2001		
Early	11.51a‡	12.20a	10.52b	*11.41§*
Late	11.40a	11.87a	8.01c	*10.43*
Average	*11.45A¶*	*12.03A*	*9.27B*	*10.92Q#*
		2002		
Early	7.55b	8.71ab	8.28ab	*8.18*
Late	8.97a	7.66ab	8.00ab	*8.21*
Average	*8.26A*	*8.19A*	*8.14A*	*8.20P*
		2003		
Early	9.94a	9.97a	9.96a	*9.96*
Late	8.81a	9.69a	9.39a	*9.30*
Average	*9.37A*	*9.83A*	*9.68A*	*9.63R*
		2001–2003		
Early	9.67a	10.29a	9.59a	*9.85*
Late	9.73a	9.74a	8.47b	*9.31*
Average	*9.70A*	*10.02A*	*9.03B*	*9.58*

† NT-R = no-till without rye; NT+R = no-till with rye; ZT+R = zone-till with rye.
‡ Planting date × rye management values within years followed by same lowercase a or b are not significantly different at $p \leq 0.05$.
§ Average yields across rye management methods did not vary significantly due to planting date at $p \leq 0.05$.
¶ Average yields for each method of rye management within years followed by same uppercase letter (A or B) are not significantly different at $p \leq 0.05$.
# Average yields in individual years followed by same uppercase letter (P, Q, or R) are not significantly different at $p \leq 0.05$.

Corn Yields

Year, planting date, and rye management affected corn yield, but herbicide programs did not (Table 3). Average corn yields were highest in 2001 and lowest in 2002 (Table 5). In 2001, temperatures and rainfall were relatively optimal for corn growth, whereas 2002 was a dry year and 2003 was a very wet year (Fig. 2).

On average over the 3 yr of this study, a 2-wk delay in planting reduced corn grain yield 0.5 Mg ha^{-1} ($p = 0.075$). However, this yield reduction with the late planting date was due to large yield reductions with ZT+R in 2001, which will be discussed below. On average from 2001–2003, no yield reduction due to late planting was observed in NT-R or in NT+R, but there were some variations in individual years. In 2001, NT-R and NT+R produced the same yields irrespective of planting date. In 2002, the early planted NT-R corn produced a lower yield than the late-planted corn. This yield reduction in early planted corn was not observed in the NT+R treatment. In 2003, however, there were no yield differences due to planting date. In the dry year 2002, the early planted corn (with a higher plant population than late-planted NT-R, see Table 4) may have depleted soil moisture, causing moisture shortages later in June, July, and August. The early planted corn in the NT+R treatment may have benefited from the mulch that helped conserve soil moisture.

Lower yields of ZT+R in 2001 were due to poor planter performance as discussed previously. Compared with early planted NT+R in 2001, yield reductions with ZT+R were 1.7 Mg ha^{-1} in early planted treatments

Table 6. Weed infestation as affected by herbicide program, corn planting date, and rye management.†

Herbicide program	Planting	Rye management‡	Weed biomass (dry weight) 2001	2002	2003
			g m^{-2}		
PREHALF	early	NT+R	5.7 abc	24.1 a	11.6 abc
		NT−R	12.4 a	16.8 abc	9.9 a-d
	late	NT+R	1.9 a-d§	10.1 a-e	20.9 ab
		NT−R	3.6 a-d	3.2 de	1.0 de
PREFULL	early	NT+R	3.9 a-d	12.1 a-d	2.9 b-e
		NT−R	2.8 a-d	10.8 ab	1.4 e
	late	NT+R	1.5 cde	6.7 a-e	10.1 c-e
		NT−R	1.5 b-e	8.1 b-e	0.0 e
POST	early	NT+R	1.3 de	2.8 b-e	8.9 abc
		NT−R	9.9 ab	2.5 e	8.8 a-d
	late	NT+R	1.5 de	3.0 c-e	7.6 a-d
		NT−R	0.4 e	2.5 b-e	11.8 a

† Biomass values within one year followed by the same letter are not significantly different at $p \leq 0.05$.
‡ NT−R = no-till without rye; NT+R = no-till with rye.
§ Hyphen indicates "inclusive of" (i.e., a-d = a, b, c, and d).

and 4.7 Mg ha^{-1} in late-planted treatments (Table 5). In late-planted treatments, larger amounts of rye residue were present, which caused more problems with ZT coulter penetration and planter performance in 2001, resulting in greatest yield reductions. In 2002 and 2003, the yield reduction with ZT+R did not occur. However, yields were never increased with ZT+R compared with NT+R. Our observation was that in-row tillage with the three-coulter system was not effective in penetrating rye residue and root mass. The yield benefits of ZT were therefore negligible in this study. Corn yields in NT-R and NT+R treatments were similar (Table 5). However, on average over the 3 yr of this study, corn yield in NT+R at the early planting date was 0.6 Mg ha^{-1} higher than that of the early planting date in NT-R (significant at $p = 0.1$). These results show that, if killed early, rye may actually increase corn yields.

Weed Control

The weed infestations were relatively low at all times, and herbicide treatments did not affect corn populations or yields. The primary weeds included a mix of common annual grasses (giant foxtail, *Setaria faberii* L., and fall panicum, *Panicum dichotomiflorum* L.) and broadleaved weeds (common lambsquarter, *Chenopodium album* L., and velvet leaf, *Abutilon theophrasti* L.), as well as yellow nutsedge. The highest weed biomass (dry weight basis) was only 24 g m^{-2} (Table 6). Low weed populations were attributed to effective prior weed management and good control by all three herbicide treatments. Although a check herbicide treatment without weed control was not included for comparison, visual weed density observations made before the POST application treatment confirmed the low weed severity in all 3 yr of the study (data not presented). Certain combinations of herbicide program, corn planting date, and rye had higher weed biomass than others (Table 6). The PREHALF program appeared inferior, whereas the PREFULL and POST treatments appeared superior.

DISCUSSION

This study has shown that considerable increases in rye biomass can be achieved by killing it at the late- instead of the early-boot stage. In the northern Mid-Atlantic region, this means a 1- to 2-wk delay of corn planting date beyond recommended dates. In our study, we did not observe corn yield reductions in no-till due to delayed planting. Other studies suggest a 5 to 10% yield reduction due to a 1- to 2-wk planting delay beyond the optimum planting date (Roth and Beegle, 2003). The additional rye biomass produced between early- and late-boot stage can help provide superior erosion control and residue additions to increase soil organic matter content. We observed a favorable decline in bulk density in late-killed rye in 2001, which offers promise to alleviate compaction. Improvements of soil quality due to the rye cover crop can be expected over time, which can result in corn yield improvements. However, because a different field was used every year, this potential benefit could not be measured. It may be possible to achieve the same rye cover crop benefits when killing it at early-boot stage as when killing it at late-boot stage if rye has been established early, but our study was not set up to answer this question, which needs additional investigation.

The rye cover crop either increased or did not impact corn yields. Clark et al. (1997b) had similar results in Maryland (Clark et al., 1997b). Studies in Ohio and Ontario, on the other hand, reported that a rye cover crop reduced yield of the following no-till corn crop (Eckert, 1988; Raimbault et al., 1990). In the Ohio study, corn yield was not reduced if the rye cover crop followed soybean instead of corn (Eckert, 1988). In this study, the previous crop was always oat that had been harvested for both grain and straw. There was very little residue left from the oat. In addition, N was not limiting in any case because the whole field was fertilized with 70 kg ha^{-1} N in March and 180 kg ha^{-1} N before corn planting, plus any additional N in starter fertilizer. This suggests that, if the preceding crop provides little residue and sufficient N is present, an early killed rye cover crop may boost corn yields and that a late-killed rye cover crop may result in similar corn yields as without a rye cover crop in our agroclimatic zone. This offers great promise for the use of rye after crops such as corn silage, soybean, and small grains where straw has been removed. Use of rye after corn grain harvest is less necessary for erosion control and organic matter addition and is more likely to result in yield reductions. Allelopathic effects of rye on corn such as those reported in Ontario (Raimbault et al., 1990) and Nebraska (Kessavalou and Walters, 1997) were not observed. It has been shown that rye varieties vary greatly in allelochemical contents (Burgos et al., 1999). In addition, the allochemicals disappear from rye residue in a period that may vary with environmental conditions (Yenish et al., 1995). Further, stress conditions increase allelochemical production (Einhellig, 1996). It is therefore possible that the (unknown) rye variety used in this trial, and the ambient conditions, led to low allelochemical production and subsequently no negative impact on corn yield. Despite the absence of yield reductions, late-killed rye may dry out the soil, resulting in planter penetration problems; be difficult to kill because the field is inaccessible in wet springs; produce very large amounts of cover crop residue that has to be managed; and increase slug injury. Producers should be aware of these potential problems and plan to avoid them.

In Ontario, in-row tillage techniques and residue removal from the row resulted in yield increases compared with no-till (Raimbault et al., 1991). Even in the years when zone-tillage performance was not compromised due to problems at planting time, it did not increase yields in the present study. The three-coulter zone-tillage system did not create zones of loose, bare soil in a rye cover crop and left large amounts of residue at the soil surface. Other in-row tillage systems can be envisioned, for example with shanks instead of coulters. It is difficult to imagine, however, how a suitable seedbed can be created with in-row tillage tools in the dense root system of a recently killed rye cover crop that has been killed at late-boot stage. Therefore, this study suggests that in-row tillage for rye cover crop management is not necessary. An appropriate set-up of the no-till planter will of course be needed. Because plant populations in late-planted corn were, on average, reduced by approximately 3000 plants ha^{-1}, a 5% increase in seeding rate is recommended when planting late. Our study did not indicate a need to increase corn plant populations when planting into a rye cover crop.

Weed control was excellent in this study due to very low weed severity and effective herbicide treatments. There were some indications of poorer weed control with a PREHALF program. Both a PRE and POST emergence weed control program provided good weed control in no-till corn. The presence or absence of rye did not influence the effectiveness of any weed control program.

CONCLUSIONS

In this study, rye killed in late-boot stage provided many additional benefits above rye killed in early-boot stage, such as reduced bulk density to alleviate compaction and increased biomass to improve soil organic matter content and provide superior erosion control. The resulting delay in planting date did not reduce corn yield, nor did the rye itself reduce corn yield. Three management factors may explain why rye cover crop management was more successful in our study compared with other studies: (i) the rye was killed 7 to 10 d before corn planting, (ii) there was little residue cover in the absence of rye, and (iii) sufficient N was present. Our results suggest in-row tillage should not be recommended in a rye cover crop system. Weed control benefits of rye did not materialize as weed pressure was very low. Therefore, both pre- and postemergence weed control programs proved effective.

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