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CROPPING SYSTEMS

Use of a Rye Cover Crop following Corn in Rotation with Soybean in the Upper Midwest

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ABSTRACT

There is a need for improved soil and water conservation in the corn (*Zea mays* L.)–soybean [*Glycine max* (L.) Merr.] rotation common to the upper Midwest, and an appropriate cover crop may fulfill this need. A corn–soybean rotation that included a rye (*Secale cereale* L.) cover crop was studied at two Minnesota locations in 2002 and 2003 to evaluate rye management method and timing for no-till soybean production. Fall-planted rye following corn harvest at Waseca and Rosemount was managed the next spring by: (i) mowing once, (ii) mowing twice, (iii) applying glyphosate herbicide once, (iv) applying herbicide twice, and (v) mowing once followed by applying herbicide, with four mow dates beginning 1 May separated by approximately 1 wk. Rye regrowth after mowing but before stem elongation in early to mid-May was similar to that of uncut rye but decreased dramatically when mowed at anthesis in early June. At Rosemount, low weed populations and the presence of the rye cover crop, when properly managed, had only a minimal affect on soybean yield, resulting in the one-pass mowing system being equally profitable as the no-rye two-pass herbicide system. At Waseca, where weed pressure was high, the rye cover crop treatments without subsequent herbicide application as well as the early one-pass herbicide applications did not provide adequate control, making these systems less profitable. Our research indicated soybean yields following a rye cover crop were often comparable to yields where no rye cover crop was grown, but economic returns were usually reduced.

The benefits of cover crop utilization to subsequent crop yield and soil health have been known for many years (Odland and Knoblauch, 1938). Cover crops reduce potential environmental risks such as soil erosion (Johnson et al., 1998; Kaspar et al., 2001) and nitrate leaching (Ditsch et al., 1993; McCracken et al., 1994; Owens et al., 2000). Cover crops also influence the cropping environment through reduction in light transmission, moderation of soil temperature fluctuations, and conservation or depletion of soil moisture (Teasdale and Mohler, 1993). Several researchers have documented the benefit of cover crops in controlling weeds (Ateh and Doll, 1996; Warnes et al., 1991; Williams et al., 1998).

Rye has been promoted as a cover crop in cool-season production systems because it is very winter hardy and begins regrowth early in the spring (Stoskopf, 1985). Other attributes that make rye an attractive cover crop include high early-spring biomass production (Bollero and Bullock, 1994), the ability to scavenge excess soil nitrate N and reduce nitrate leaching following corn (Staver and Brinsfield, 1998; Strock et al., 2004), weed suppression for up to 5 wk from rye mulch (Liebl et al., 1992; Williams et al., 1998), and the production of allelopathic compounds that increase weed suppression (Barnes and Putnam, 1987).

Despite the potential benefits of rye, its adoption as a cover crop in the corn–soybean rotation has been minimal. The limited use of rye can be attributed to cost of establishment and termination as well as possible interference with the subsequent crop growth. When rye was used as a cover before corn, yield was reduced in part due to N immobilization (Tollenaar et al., 1993; Vaughan and Evanylo, 1998; Wagger, 1989). Soybean grown following rye has not shown the same yield reductions as corn. In Ontario, Wagner-Riddle et al. (1994) found that while soybean growth was reduced early in the season, there was no yield difference at harvest. Bauer (1989) reported that soybean yield was not reduced when rye was managed with a herbicide but was reduced when rye was mowed without subsequent application of a herbicide due to rye regrowth. Studies by Bauer (1989) and Eckert (1988) indicated that soybean stand establishment was reduced when planted into rye residue. Bauer (1989) also reported delayed physiological development of soybean with rye due to reduced soil water content and that there was a tradeoff between increased weed control due to greater rye biomass and the potential interference with soybean growth. This tradeoff depended on when the rye residue was managed. Liebl et al. (1992) found that managing rye in late May reduced soybean stands compared with when rye was managed in early May but did increase weed control. In Mississippi, Reddy (2003) found that a rye cover-crop–based soybean production system using herbicides was less profitable compared with no-cover-crop–based production systems using herbicides.

The ability to manage rye with mowing is necessary for both organic production systems and reduced-herbicide input systems. While many studies have reported on various components of rye cover crop systems, few studies have given a comprehensive system analysis of mechanical and reduced-herbicide cover crop management, especially at late-fall rye planting dates and early-spring soybean planting dates common to the upper Midwest. The objectives of this study were to evaluate the timing and method (combinations of herbicide and mow-

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Abbreviations: AMS, ammonium sulfate; COCB, common cocklebur; COLQ, common lambsquarter; CORW, common ragweed; GIFT, giant foxtail; GIRW, giant ragweed; trt, treatment.

ing) of rye cover crop management in a corn–soybean rotation and the many factors that contribute, both positively and negatively, to system productivity and profitability compared with conventional soybean production. We hypothesize that rye management method and timing of a fall-seeded rye cover crop could be used to minimize interference of rye with no-till soybean. The above objectives were addressed by: (i) measuring rye biomass, N accumulation, and regrowth at four mowing dates; (ii) documenting soybean yield response to systems without rye and systems with rye managed on four dates with mowing and/or the herbicide glyphosate [*N*-(phosphonomethyl)glycine]; and (iii) comparing the weed species present with each of the management strategies.

MATERIALS AND METHODS

The study was conducted at the Southern Research and Outreach Center near Waseca, MN, and at the University of Minnesota Outreach, Research, and Education (UMORE) Park near Rosemount, MN, in 2001–2002 and 2002–2003. The soil type at Waseca is a poorly drained Webster clay loam (fine-loamy, mixed mesic Typic Endoaquoll), and the soil type at Rosemount is a well-drained Waukegan silt loam (fine silty over sandy, mixed mesic Typic Hapludoll). The rye cultivar Rymin was fall-seeded on 18 and 25 Oct. 2001 at Waseca and Rosemount, respectively. In 2002, the rye cultivar Homil21 was seeded on 11 Oct. and 1 Nov. at Waseca and Rosemount, respectively. Rye was solid-seeded at 125 kg ha^{-1} into corn residue with a no-till drill at a row spacing of 19.3 cm at Waseca and 20.3 cm at Rosemount.

The 22 treatments (trts) in this study involved two soybean planting dates and different combinations of five rye and weed management strategies [(i) applying herbicide twice (trts 1–3, 18), (ii) applying herbicide once (trts 4–6, 19), (iii) mowing once followed by a herbicide application (trts 7–9, 20), (iv) mowing twice (trts 13–15), and (v) mowing once (trts 10–12, 21)] at four dates separated by approximately 1 wk (Table 1). Treatments 1 through 15 involved early planted soybean, and trts 18 through 21 involved late-planted soybean. Treatments 16, 17, and 22 were no-rye control trts with trts 16 and 17 having early planted soybean with herbicide applied once and twice, respectively, and trt 22 having late-planted soybean with herbicide applied twice. The rationale for the trts was that when rye is mowed too early in its development, it could regrow, perhaps requiring subsequent control with a herbicide at a later date, and that one herbicide application would adequately control rye but perhaps not the later-emerging weeds.

The experimental design at each location was a randomized complete block with four replicates. Plot size was 3.6 by 15.2 m at Waseca and 3.6 by 12.2 m at Rosemount. Field operation dates are listed in Table 1. Growth stage of the rye at each management date was determined using the decimal code for cereals developed by Zadoks et al. (1974) and refined by Tottman (1987). Primary and secondary weed management with a herbicide was with glyphosate at a rate of 1.41 kg a.i. ha^{-1} plus ammonium sulfate (AMS) at 2.8 kg ha^{-1}. A flail mower was used to mow the rye both years at Waseca, and a lawn mower and flail mower were used at Rosemount in 2002 and 2003, respectively. For certain trts (trts 13, 14, and 15) a flail mower was used to cut rye a second time approximately 5 cm above the soybean seedlings. Data for these trts are not reported for Rosemount in 2002 as cutting height was too low, which resulted in the clipping of many soybean plants and consequently a very poor soybean stand.

Soybean was planted at approximately 493 000 seeds ha^{-1} with a no-till drill on row widths of 20.3 cm at Rosemount and 25.4 cm at Waseca. In 2002, the cultivar Asgrow 2034 was planted on 10 and 24 May at Waseca and 10 May and 5 June at Rosemount as well as 15 and 29 May at Waseca in 2003. The cultivar Pioneer 91BO3 was planted 5 and 23 June at Rosemount in 2003 (Table 1). All soybean cultivars were glyphosate resistant. Planting was delayed at Rosemount in 2003 due to slow rye development and wet field conditions.

Table 1. Treatments and field activity dates in a study evaluating soybean grown following a rye cover crop at Rosemount and Waseca, MN, in 2002 and 2003.

			Soybean planting date						Primary rye/weed management					Secondary weed management			
			Rosemount		Waseca				Rosemount		Waseca			Rosemount		Waseca	
Trt	System		2002	2003	2002	2003	Rye control date		2002	2003	2002	2003		2002	2003	2002	2003
1	Rye	E†	14 May	5 June	14 May	15 May	1	H‡	4 May	13 May	1 May	1 May	H	12 June	1 July	13 June	20 June
2	Rye	E	14 May	5 June	14 May	15 May	2	H	8 May	29 May	8 May	7 May	H	12 June	1 July	13 June	20 June
3	Rye	E	14 May	5 June	14 May	15 May	3	H	15 May	2 June	20 May	14 May	H	12 June	1 July	13 June	20 June
4	Rye	E	14 May	5 June	14 May	15 May	1	H	4 May	13 May	1 May	1 May	–§	–	–	–	–
5	Rye	E	14 May	5 June	14 May	15 May	2	H	8 May	29 May	8 May	7 May	–	–	–	–	–
6	Rye	E	14 May	5 June	14 May	15 May	3	H	15 May	2 June	20 May	14 May	–	–	–	–	–
7	Rye	E	14 May	5 June	14 May	15 May	1	M¶	4 May	13 May	1 May	1 May	H	12 June	1 July	13 June	20 June
8	Rye	E	14 May	5 June	14 May	15 May	2	M	8 May	29 May	8 May	7 May	H	12 June	1 July	13 June	20 June
9	Rye	E	14 May	5 June	14 May	15 May	3	M	15 May	2 June	20 May	14 May	H	12 June	1 July	13 June	20 June
10	Rye	E	14 May	5 June	14 May	15 May	1	M	4 May	13 May	1 May	1 May	–	–	–	–	–
11	Rye	E	14 May	5 June	14 May	15 May	2	M	8 May	29 May	8 May	7 May	–	–	–	–	–
12	Rye	E	14 May	5 June	14 May	15 May	3	M	15 May	2 June	20 May	14 May	–	–	–	–	–
13	Rye	E	14 May	5 June	14 May	15 May	1	M	4 May	13 May	1 May	1 May	M	12 June	2 July	13 June	12 June
14	Rye	E	14 May	5 June	14 May	15 May	2	M	8 May	29 May	8 May	7 May	M	12 June	2 July	13 June	12 June
15	Rye	E	14 May	5 June	14 May	15 May	3	M	15 May	2 June	20 May	14 May	M	12 June	2 July	13 June	12 June
16	No rye	E	14 May	5 June	14 May	15 May	–	–	–	–	–	–	H	12 June	1 July	13 June	20 June
17	No rye	E	14 May	5 June	14 May	15 May	–	H	8 May	29 May	8 May	7 May	H	12 June	1 July	13 June	20 June
18	Rye	L#	7 June	23 June	30 May	29 May	4	H	22 May	17 June	28 May	20 May	H	3 July	29 July	27 June	3 July
19	Rye	L	7 June	23 June	30 May	29 May	4	H	22 May	17 June	28 May	20 May	–	–	–	–	–
20	Rye	L	7 June	23 June	30 May	29 May	4	M	22 May	17 June	28 May	20 May	H	3 July	29 July	27 June	3 July
21	Rye	L	7 June	23 June	30 May	29 May	4	M	22 May	17 June	28 May	20 May	–	–	–	–	–
22	No rye	L	7 June	23 June	30 May	29 May	–	H	22 May	17 June	28 May	20 May	H	3 July	29 July	27 June	3 July

† E = early planting date.
‡ H = herbicide.
§ – = No management.
¶ M = mowed.
 # L = late planting date.

Rye aboveground biomass measurements were taken weekly from previously uncut rye beginning the third week of April and continued until the end of May from 0.23 and 0.24 m^{-2} quadrants at Waseca and Rosemount, respectively. Rye regrowth biomass measurements were taken at weekly intervals 1 wk after primary mowing for the four rye management dates and continued through mid-June in 2002 and through mid-July in 2003. The biomass samples were oven-dried at 48°C for 72 h. The samples taken from the previously uncut rye were ground and analyzed with NIRSystems 6500 scanning monochrometer (NIRSystem Incorporated, Silver Springs, MD). Twenty samples were selected as a monitoring set by WINSI II software (Intrasoft International, Port Matilda, PA) for calibration. Nitrogen content was estimated using a modified partial least squares regression using "Global Calibration" function of the WINSI II software.

Beginning in late May, soil samples were taken periodically, based on rainfall events, to determine soil moisture content. Soil samples were not taken if a significant rainfall event had recently occurred. In 2002, few samples were taken due to the high rainfall in late May and June (Table 2). Rainfall events were less frequent in 2003, and samples were colleted through August. The soil samples were obtained from both rye and no-rye trts to a depth of 60 cm, except in 2003 at Rosemount where cores were taken to a depth of 45 cm. Three soil cores per plot were divided into sections of 0 to 15, 15 to 30, and 30 to 45 or 30 to 60 cm; combined; thoroughly mixed; and subsampled. These soil subsamples were weighed, oven-dried at 48°C for 72 h, and reweighed. Growing degree units (GDU) were calculated beginning 1 March using a base temperature of 0°C (Nuttonson, 1958).

Weeds were sampled the second week of June at Waseca both years and at Rosemount in 2003. The Rosemount site was not sampled in June 2002 due to low weed populations. Weed population and aboveground biomass were determined from three 0.03-m^2 quadrants per plot at Waseca in 2002 and from four 0.29-m^2 quadrants per plot at Waseca and Rosemount in 2003 for trts where rye was mowed and the no-rye control trts (trts 10, 11, 12, 16, and 21). Weed populations and aboveground biomass were again sampled at both locations from all plots at the end of August from two 0.29-m^2 quadrants at Waseca in 2002 and 2003 and four 0.29-m^2 quadrants at Rosemount in 2003. Low weed pressure at Rosemount in 2002 allowed all of the weeds in each plot to be counted, and a representative sample of weeds from each species was collected, dried, and weighed to determine biomass.

Soybean stand establishment was determined approximately one month after planting from a 1-m segment of three rows per plot at both locations. Soybean aboveground biomass and height were determined at the end of July when the soybean plants had reached V5 to V6 growth stage for early planted soybean and V2 to V3 for late-planted soybean (Fehr and Caviness, 1977) by selecting three and five representative plants from each plot in 2002 and 2003, respectively. One week before soybean harvest, pod number was determined from five randomly selected representative plants per plot for selected trts (trts 1, 7, 10, 17, 21, and 22) at both locations in 2002 and for all trts at both locations in 2003. Soybean plants were scored for lodging (1 = no lodging and 5 = completely prostrate) just before harvest. In October, soybean was mechanically harvested with a small-plot combine, and seed moisture, grain yield (adjusted to 130 g H_2O kg^{-1}), test weight, and 100-seed weight were determined.

Costs associated with each trt were estimated based on the following assumptions for each trt. The cost of rye seed was \$0.20 kg^{-1}. Costs for rye planting and mowing were \$31.40 and \$18.5 ha^{-1}, respectively, and represent a custom rate charge (Lazarus and Selley, 2003). Herbicide costs were \$26.50 ha^{-1} for glyphosate, \$1.23 ha^{-1} for AMS, and \$12.30 ha^{-1} for application. A technology fee for glyphosate-tolerant soybean seed of \$19.75 ha^{-1} was applied to trts that consisted of at least one herbicide application but not to trts that did not receive a herbicide application. Soybean grain price of \$0.22 kg^{-1} was calculated using a weighted price where 50% of the total price was the average November cash price, 25% was the March Chicago Board of Trade (CBOT) futures price (\$0.24 basis), and 25% was the July CBOT futures price (\$0.04 basis) on 21 Nov. 2003 (Palle Pedersen and Joe Lauer, personal communication, 2003). November cash price was determined based on the past 5 yr of data recorded by Minnesota Agricultural Statistics Service (Minnesota Dep. of Agric., 2002).

Statistical analysis was conducted with PROC GLM in SAS (SAS Inst., 1995). Years and locations were considered random for soybean yield and system profitability. All other effects were considered fixed. Soil water content was analyzed separately by year and location for each specific sample date for the three soil sampling depths. Weed counts were transformed with log transformation to achieve homogeneity of variance (Oehlert, 2000) and were analyzed separately by year and location due to extreme differences in weed populations and species type. Weed biomass of early weed samples was log-transformed and analyzed separately by year to achieve constant variance. Weed data from Rosemount was not analyzed due to low numbers. Plant height and biomass were analyzed separately for early and late-planted soybean but were combined over years. Soybean yield and system profitability data were combined over year and location after constant variance had been determined.

Table 2. Mow date, growth stage, biomass, growing degree units, N uptake, and concentration at the four rye management dates.

Rye control date	Waseca: Mow date	Growth stage†	Rye biomass	GDU‡	N uptake	N conc.	Rosemount: Mow date	Growth stage	Rye biomass	GDU	N uptake	N conc.
			kg ha^{-1}		kg ha^{-1}	g kg^{-1}			kg ha^{-1}		kg ha^{-1}	g kg^{-1}
2002												
1	1 May	23	375	694	14.2	38.0	1 May	23	489	735	16.2	33.2
2	8 May	29	851	757	28.9	34.1	8 May	29	728	801	21.3	29.3
3	20 May	34	2185	876	65.5	30.1	15 May	31	1033	874	27.6	26.8
4	28 May	53	3768	999	73.8	19.6	22 May	33	1798	954	38.5	21.4
2003												
1	1 May	22	151	520	5.7	38.3	13 May	25	147	654	5.0	34.2
2	7 May	24	222	593	8.2	37.0	23 May	32	414	794	10.9	26.3
3	14 May	27	522	672	17.3	33.1	2 June	53	1424	966	28.1	19.7
4	20 May	31	986	767	20.7	21.0	17 June	65	2928	1255	43.0	14.7

† Based on the decimal code of Tottman (1987).
‡ GDU, growing degree units with base 0°C, calculated from date of rye planting.

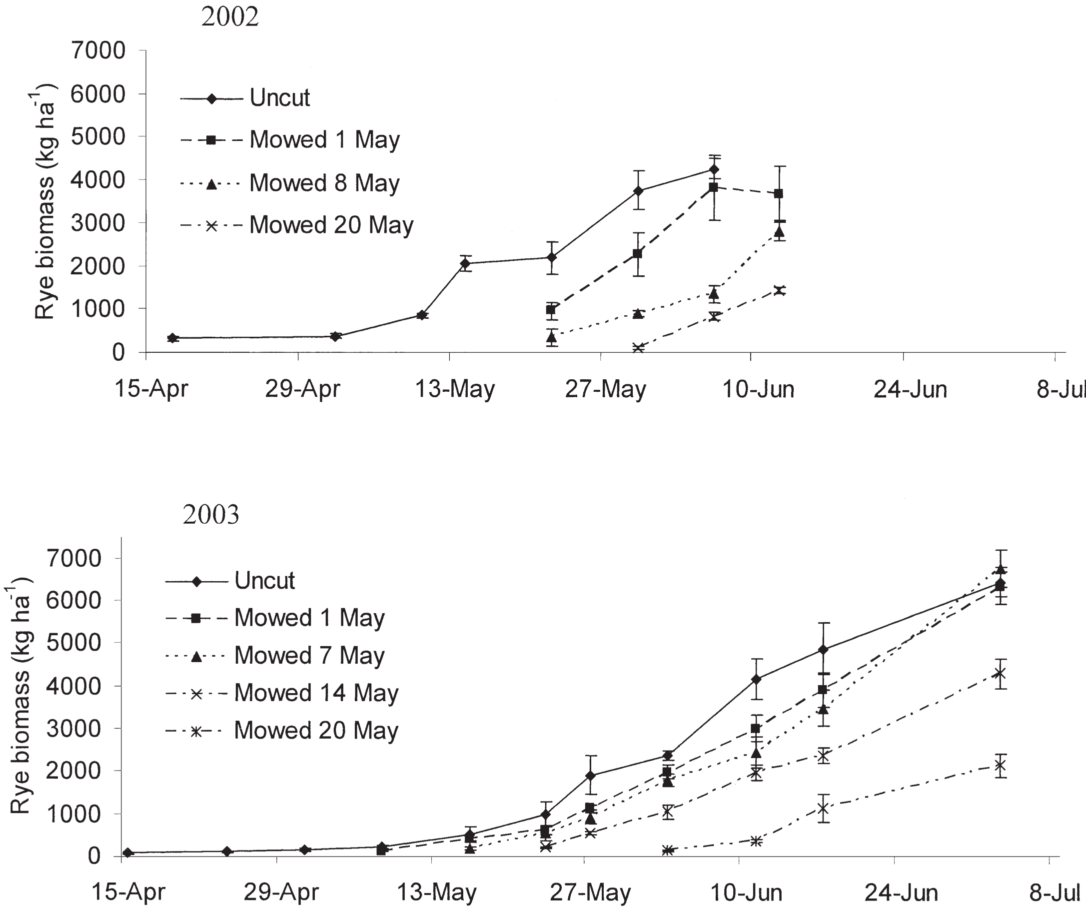

Fig. 1. Aboveground biomass of uncut rye and regrowth biomass of mowed rye at Waseca 2002 and 2003. Vertical bars represent ±1 standard error of the mean.

RESULTS AND DISCUSSION

Rye Growth, Regrowth, and Nitrogen Accumulation

Spring rye growth differed by year and location and was influenced by time of fall planting and growing conditions (Table 2). Growth was similar at both locations in 2002 but was reduced at both locations in 2003, with the greatest reduction occurring at Rosemount due to the late planting date (1 Nov.). Rye growth was exponential throughout May (Fig. 1 and 2). At Waseca, by 15 April, rye biomass was 0.31 and 0.06 Mg ha^{-1} in 2002 and 2003, respectively, and increased by 1 May to 0.38 and 0.15 Mg ha^{-1} in 2002 and 2003, respectively (Fig. 1). At Rosemount, by mid-April in 2002, rye biomass was 0.28 Mg ha^{-1}, whereas in 2003, it was only 0.01 Mg ha^{-1}, and by the first mow date in 2002 (1 May), it was 0.48 Mg ha^{-1} but only 0.15 Mg ha^{-1} at the first mow date in 2003 (16 May) (Fig. 2).

Regrowth of rye from mowed trts with no subsequent herbicide application (trts 10, 11, and 12) was 3.8, 2.7, and 1.4 Mg ha^{-1} by the middle of June in 2002, averaged across locations for the first three rye management dates, respectively (Fig. 1 and 2). Regrowth in 2003 by the middle of July averaged 6.3, 6.0, 4.3, and 2.1 Mg ha^{-1} at Waseca (Fig. 1) and 2.9, 2.2, 1.5, and 0.05 Mg ha^{-1} at Rosemount (Fig. 2) for the four rye management dates (trts 10, 11, 12, and 21), respectively. Mowing rye early in the vegetative stage reduced regrowth potential very little, whereas mowing rye after anthesis almost completely controlled regrowth (Fig. 2). Our results agree with the work of Bauer (1989) and Wilkins and Bellinder (1996) in that rye regrowth was reduced by later mowing dates on advanced rye growth stages.

Nitrogen accumulation in the aboveground biomass of previously uncut rye at Waseca was 74 and 21 kg N ha^{-1} by 28 May 2002 and 22 May 2003, respectively, whereas at Rosemount, it was 38 and 43 kg N ha^{-1} by 22 May 2002 and 17 June 2003, respectively (Table 2). These values are similar to those reported by Kessavalou and Walters (1999) in Nebraska. Waiting until later in the season to manage the rye cover crop is beneficial from an environmental standpoint by allowing time for greater N immobilization as well as from a weed management standpoint by taking advantage of the rye biomass to suppress weed growth; however, increased rye biomass accumulation can result in reduced soil water content, which may contribute to poor soybean establishment and growth (Eckert, 1988).

Soil Water Content

Precipitation was above normal in June 2002 at both locations, and by June 6, no soil water content differ-

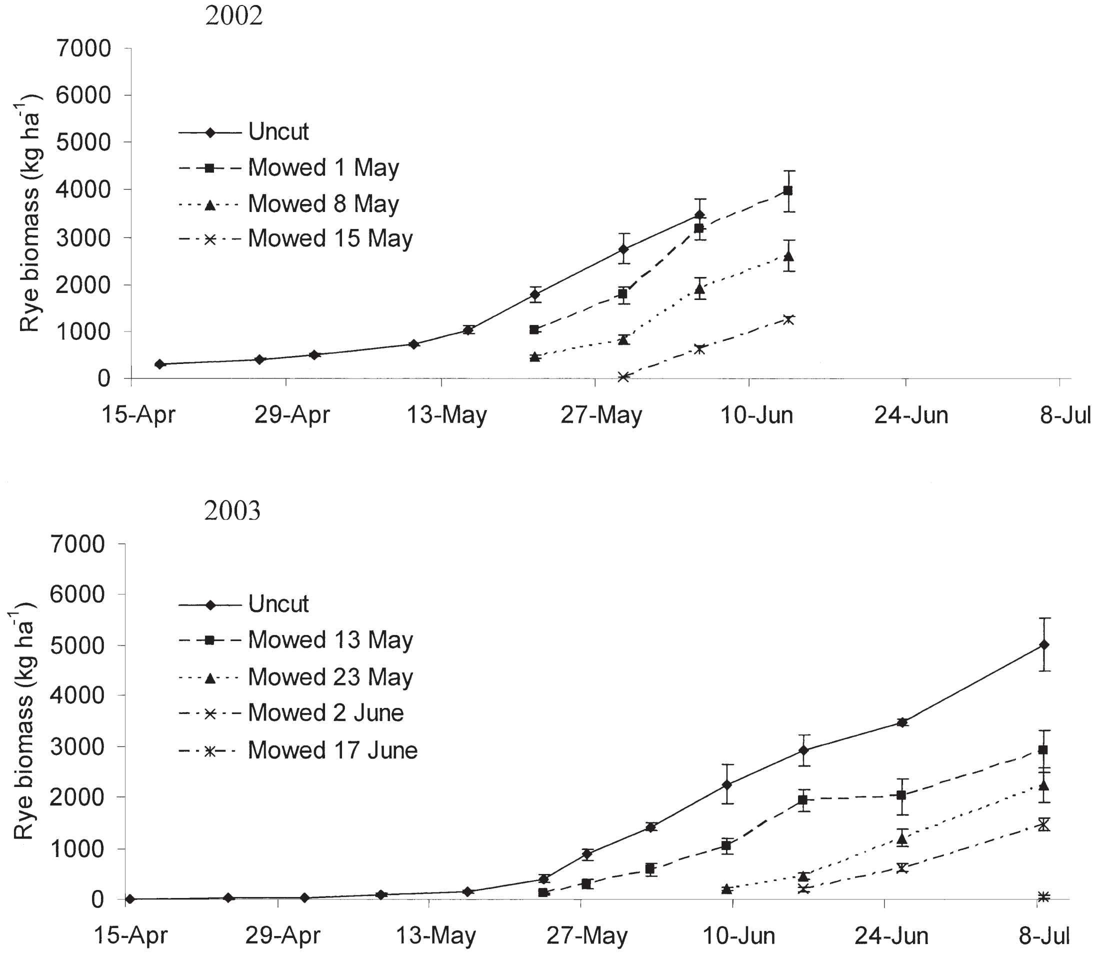

Fig. 2. Aboveground biomass of uncut rye and regrowth of mowed rye at Rosemount 2002 and 2003. Vertical bars represent ±1 standard error of the mean.

ences were detected in the soil profile between where rye was grown and where rye was not grown (data not shown). Thus, the rye cover crop in 2002 did not contribute to any negative soil water content problems for the subsequent soybean crop. In 2003 at both locations, precipitation was below normal most months from January through August, and conditions were quite dry in July and August (Table 3). In 2003, significant differences in soil water content between where rye was grown and not grown were detected in early to mid-July at the 30- to 60-cm soil depth (Fig. 3 and 4), indicating rye was influencing soil water content to that depth. We speculate the reduction in available soil water content by rye uptake in 2003 was high enough to adversely influence soybean yields of trts where rye was managed late (trts 18–21) (Table 4).

Soybean Establishment

In general, soybean plant population was adequate for all trts and not thought to be yield limiting (Table 5). The exception was Rosemount in 2003, which had lower stands by about 30% compared with Rosemount in 2002 and Waseca in both years. Establishment was reduced for all trts (<400 000 plants ha^{-1}) at Rosemount in 2003 due to late planting date (Table 1) and dry soil conditions (Table 3 and Fig. 4), and the reduced plant populations may have contributed to lower yields for some trts. Eckert (1988) and Liebl et al. (1992) also reported reduced soybean populations when rye management was delayed. At Waseca, soybean establishment was reduced when rye was mowed compared with when herbicide was used or with the no-rye trts, but there was no stand difference between rye controlled by a herbicide and no-rye trts (Table 5). Plant populations, however, were dense enough to support high yields each year regardless of trt.

Weed Population and Biomass

Weed population and biomass were monitored for selected trts in June (data not shown) and for all trts in late August (Table 6). Weed populations at Rosemount were very low each year for all trts, with all weed species occurring at levels less than 1 plant m^{-2}. Because of the low weed population at Rosemount, weed pressure did not influence soybean yield. It was a very different situation at Waseca.

In June 2002 at Waseca, weed pressure was very high. In the no-rye trts, giant ragweed (GIRW), common ragweed (CORW), common lambsquarter (*Chenopodium album*, COLQ), and common cocklebur (COCB) all had

Table 3. Monthly temperature, precipitation, and departure from long-term average for October through August 2001–2002 and 2002–2003 at Rosemount and Waseca, MN.

	Rosemount				Waseca			
	Temperature		Precipitation		Temperature		Precipitation	
Month	Average	Departure from normal†	Average	Departure from normal	Average	Departure from normal	Average	Departure from normal
	°C		cm		°C		cm	
				2001–2002				
October	9.2	(0.1)‡	3.3	(2.3)	8.7	(0.2)	2.8	(3.4)
November	8.0	7.3	7.0	3.1	7.8	7.6	6.4	2.0
December	−2.4	5.0	1.9	(0.7)	−2.6	6.2	1.8	(1.6)
January	−4.1	6.4	1.2	(1.5)	−5.3	6.3	1.2	(2.3)
February	−2.0	4.6	0.9	(1.1)	−3.4	4.4	1.3	(1.1)
March	−3.9	(4.0)	3.5	(1.2)	−4.2	(3.2)	4.4	(2.0)
April	7.6	(0.5)	8.2	2.3	7.1	(0.1)	7.2	(1.0)
May	12.6	(2.6)	7.2	(1.0)	12.3	(2.3)	4.3	(5.7)
June	21.7	1.5	21.1	10.1	21.5	1.6	18.2	7.4
July	25.0	2.2	13.2	2.9	24.0	2.2	6.8	(4.5)
August	21.6	0.2	21.1	10.8	20.3	(0.2)	15.4	3.8
				2002–2003				
October	5.4	(3.8)	10.7	5.3	5.4	(3.3)	11.3	4.9
November	0.6	0.3	0.2	(4.7)	−0.3	0.1	0.7	(5.2)
December	−3.2	4.2	0.5	(2.0)	−3.9	4.6	0.7	(2.9)
January	−9.3	1.2	0.6	(2.1)	−10.7	1.0	1.0	(2.6)
February	−9.1	(2.4)	1.4	(0.6)	−7.3	0.5	1.6	(0.8)
March	−0.4	(0.4)	3.7	(1.1)	0.8	1.8	5.5	(0.8)
April	9.1	0.9	6.1	0.2	8.3	1.1	4.6	(3.6)
May	14.3	(0.9)	15.6	7.4	13.7	(0.9)	9.0	(1.1)
June	20.1	(0.2)	11.8	0.8	19.2	(0.7)	9.8	(0.9)
July	23.2	0.3	5.2	(5.0)	21.7	(0.2)	8.1	(3.3)
August	24.1	2.6	2.8	(7.4)	21.9	1.4	4.4	(7.2)

† Departure from normal from 1971–2000.
‡ Numbers in parentheses represent a reduction from normal for temperature and precipitation.

more than 25 plants m^{-2} (data not shown). The presence of rye reduced COLQ and COCB populations nearly fourfold but had no influence on GIRW or CORW populations. The presence of rye also reduced the biomass of all four species relative to the no-rye trt. In June 2003 at Waseca, the populations of these four species was considerably lower than in 2002, with no-rye trts having fewer than 5 plants m^{-2} of each of these four species. The presence of rye had no measurable influence on the population of these species but did reduce the biomass of COLQ and COCB (De Bruin, 2004).

By late August at Waseca, after secondary weed management, weed populations were very low each year when the herbicide glyphosate was applied to trts for secondary weed management, whereas trts without secondary weed management had larger weed populations that probably influenced soybean yield (Table 6). In both 2002 and 2003, the trts with only one early herbicide application (trts 4–6) had the greatest weed biomass—more than the trts that were mowed only once (trts 10–12) even though these latter trts tended to have as many or more plants per square meter. One early herbicide application did not give adequate season-long control of the later-emerging weed species (Buhler et al., 1997). Within each year, the dominant weed species varied depending on type and timing of rye management. The dominant weed species by late August at Waseca in 2002 were GIRW and CORW. Treatments with the early application of the one-time-only herbicide (trts 4–6, 19) as well as the mowing-only trts (trts 10–15, 21) had the most GIRW. These same mowing-only trts had the most CORW (Table 6). The dominant weed species by late August at Waseca in 2003 were COCB and giant foxtail (GIFT). Treatments with the early application of the one-time-only herbicide (trts 4–6, 19) as well as the mowing-only trts (trts 10–15, 21) had the most GIFT and the most CORW (Table 6). Comparing the one-time-only herbicide trts (trts 4–6, 19), the later the herbicide was applied, the lower the GIRW population, but this was not observed with CORW, COCB, or GIFT. The later the herbicide was applied, the lower the GIRW, CORW, and GIFT biomass. This was not observed with COCB.

Weed population and biomass results from Waseca, where high weed populations occurred, indicated rye did not control weed populations for the entire growing season unless there was a late herbicide application. Other studies (Liebl et al., 1992; Bauer, 1989; Williams et al., 1998) reported a reduction in early-season population and biomass of the relatively small-seeded redroot pigweed (*Amaranthus retroflexus*), COLQ, and GIFT with the use of rye as a cover crop. Our study, however, indicated rye did not provide adequate season-long suppression of GIRW, CORW, and COCB.

Soybean Yield and Yield Parameters

In this study, differences in weed pressure, precipitation, and the date of the late-planted soybean had a profound influence on soybean yields (Table 4). At Waseca, soybean yield both years was reduced when a herbicide was not used for late-season weed control due to high weed densities. In 2002, soybean planting date had no impact on soybean yield, with late-planting-date yields

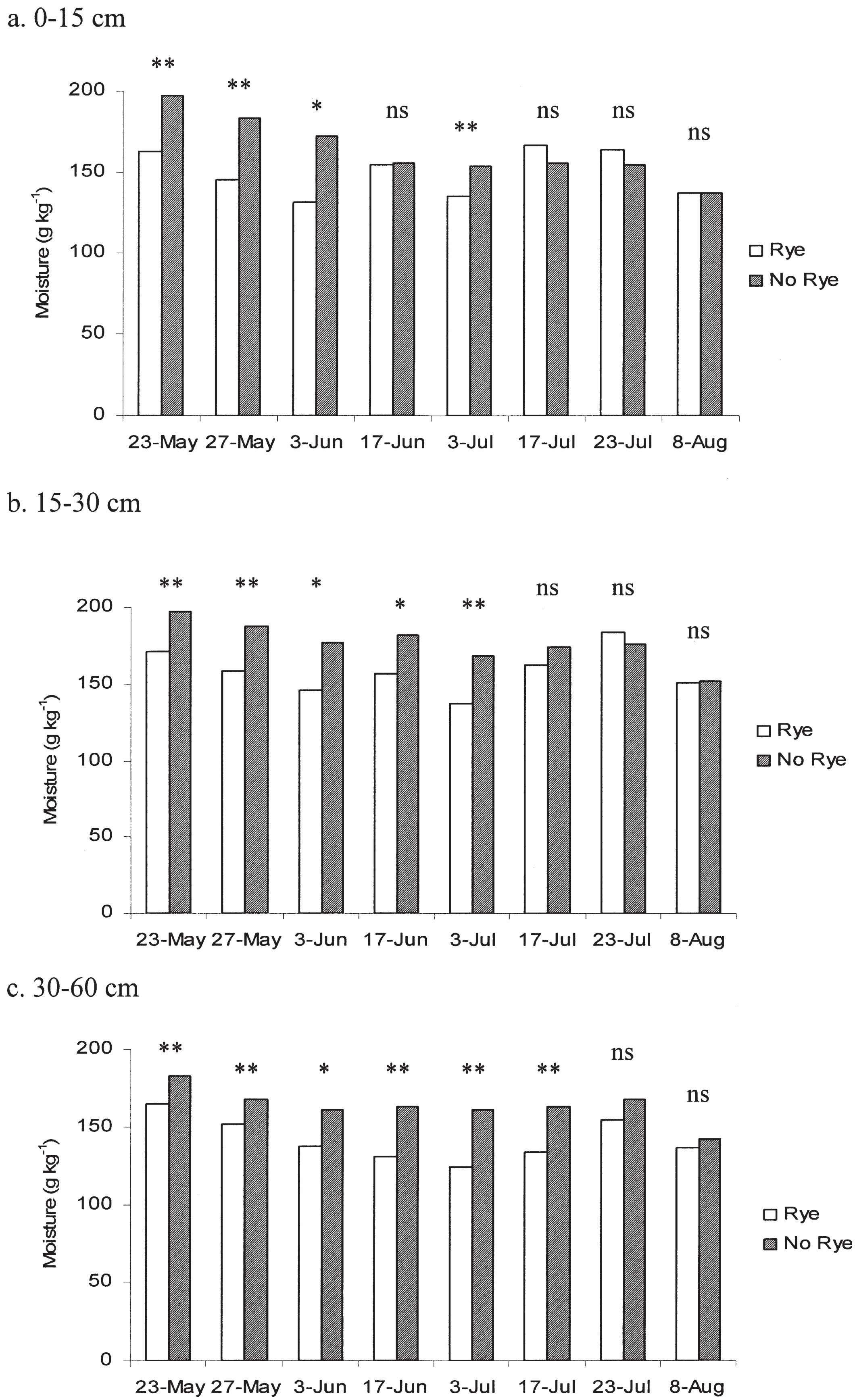

Fig. 3. Soil moisture from uncut rye and no-rye treatments at Waseca in 2003: (a) 0 to 15 cm, (b) 15 to 30 cm, and (c) 30 to 60 cm. For each depth, * and ** indicate significance at $P = 0.05$ and $P = 0.01$, respectively, and ns indicates nonsignificant at $P = 0.05$.

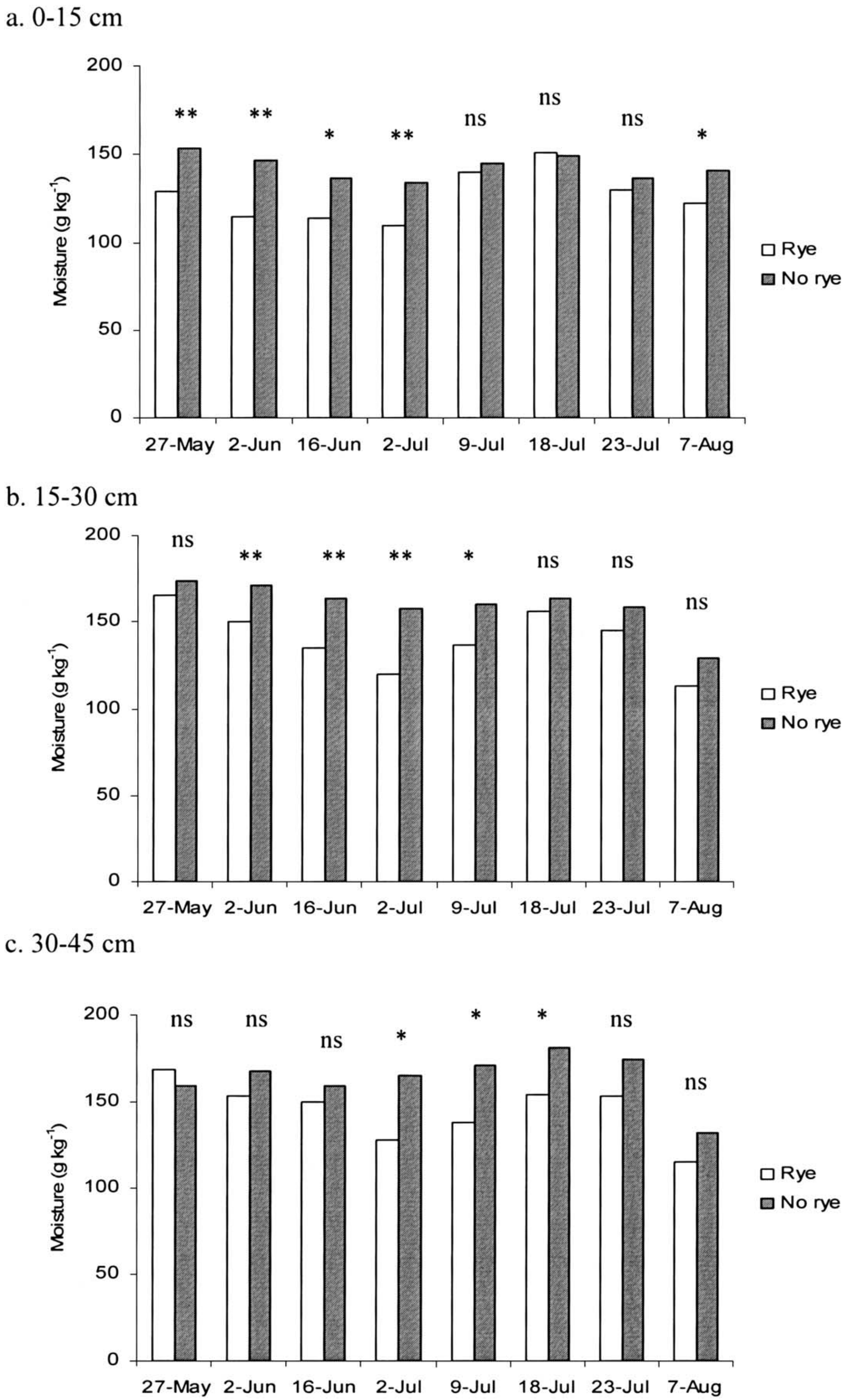

Fig. 4. Soil moisture from uncut rye and no-rye treatments at Rosemount in 2003: (a) 0 to 15 cm, (b) 15 to 30 cm, and (c) 30 to 45 cm. For each depth, * and ** indicate significance at $P = 0.05$ and $P = 0.01$, respectively, and ns indicates nonsignificant at $P = 0.05$.

Table 4. Soybean yield and economic return for the treatments (trt) at Rosemount and Waseca, MN.

Trt	Yield				Cost per trt†	Economic return‡			
	Rosemount		Waseca			Rosemount		Waseca	
	2002	2003	2002	2003		2002	2003	2002	2003
	Mg ha^{-1}				$ ha^{-1}				
1	2.94	1.42	2.89	2.66	157	489	155	477	427
2	2.81	1.30	2.90	2.55	157	458	129	479	402
3	3.15	1.60	3.31	2.18	157	535	194	569	322
4	3.01	1.63	0.30	1.16	117	544	241	(51)	137
5	2.92	1.51	0.78	0.95	117	524	214	55	91
6	3.02	1.74	1.06	1.28	117	545	266	115	163
7	2.78	1.50	2.13	1.74	136	473	193	461	240
8	2.96	1.50	2.69	1.97	136	513	192	453	297
9	3.04	1.50	2.92	2.19	136	531	192	504	344
10	2.15	1.04	0.37	0.73	76	395	153	5	85
11	2.50	1.27	1.29	1.21	76	473	203	65	190
12	3.01	1.04	0.83	0.99	76	585	153	106	142
13	–§	1.21	0.46	1.09	94	–	172	6	156
14	–	1.23	0.49	1.17	94	–	177	43	162
15	–	1.21	0.88	1.14	94	–	172	84	157
16	2.83	1.51	2.84	2.47	60	562	270	562	483
17	2.75	1.44	2.57	2.68	100	503	216	478	487
18	2.45	1.05	3.14	2.21	157	380	73	531	328
19	2.55	1.16	0.74	1.14	117	442	138	46	114
20	2.24	0.57	3.01	1.75	136	356	(12)	525	248
21	2.41	0.49	0.62	1.09	76	452	32	59	164
22	2.58	1.18	3.58	1.85	100	467	158	685	306
Avg.	2.74	1.28	1.78	1.65					
LSD		0.47					46		
ANOVA									
Year (Y)		***					NS¶		
Location (L)		***					NS		
Y × L		***					***		
Block (Y × L)		NS					NS		
Treatment (T)		***					***		
Y × T		***					***		
L × T		***					***		
Y × L × T		***					***		

*** Significant at the $P = 0.001$ probability level.
† Represents cost of rye seed, rye planting and mowing, herbicide, and herbicide application.
‡ Represents yield times soybean price minus cost per treatment. See text for a more detailed explanation.
§ Data not available due to mowing error where the rye was mowed too close to ground level.
¶ NS = nonsignificant at $P = 0.05$.

equal to or greater than early-planting-date yields. The highest-yielding trts in 2002 included those with secondary weed management with a herbicide (trts 1–3, 7–9, 16–18, 20, and 22). In 2003, the late-planting-date yields were lower than the early-planting-date yields due in part to the dry growing July and August (Table 3). The highest-yielding trts in 2003 included those planted early that had secondary weed management with a herbicide (trts 1–3, 16, and 17) where rye was not allowed to regrow and thus compete with soybean for soil moisture.

In both years at Rosemount, weed populations were very low and probably had no impact on soybean yield. The second planting date at Rosemount, however, resulted in reduced soybean yield both years compared with the early planting date. It should be noted that in both years, the second planting date at Rosemount was a week or more later than the second planting date at Waseca (Table 1). The highest-yielding trts in 2002 included all the early planted trts except the two trts where rye was mowed once on the first and second rye control date (trts 10 and 11). The highest-yielding trts in 2003 included the early planted trts where a herbicide was used (trts 1–9, 16, and 17).

In 2003, pod number per plant (Table 5), along with plant height and biomass (data not shown), were lowest for trts where the rye was mowed and no subsequent herbicide was applied (trts 10–15) due to weed and rye regrowth that competed with the soybean. Differences for seed weight were detected between trts at both locations in both years but could not be explained by rye/weed management date or method at either location (Table 5).

Our results match Bauer's (1989) findings that soybean yield was reduced when rye was mowed early in the season and no additional herbicide was applied as well as results reported by Bauer (1989) and Wagner-Riddle et al. (1994) that no yield reduction was noted when rye was controlled with a herbicide followed by later herbicide application for weed control. Mowing the rye before anthesis, with no subsequent herbicide application, allows for excessive rye regrowth that can compete with soybean for soil moisture and nutrients.

Economic Analysis

The estimated cost associated with each trt (Table 4) was the lowest for the no-rye one-herbicide application trt (trt 16; \$60 ha^{-1}), the rye mowed once trts (trts 10–12, 21; \$76 ha^{-1}), and the rye mowed twice trts (trts 13–15; \$94 ha^{-1}). Certified organic production practices could involve the trts where the rye is mowed and no herbicide is applied, thus making this practice a low-cost option for organic producers.

Table 5. Soybean plant population, 100-seed weight, and pod per plant for the treatments at Rosemount and Waseca, MN.

	Plant population				100-seed weight				Pods per plant	
	Rosemount		Waseca		Rosemount		Waseca		Rosemount	Waseca
Trt	2002	2003	2002	2003	2002	2003	2002	2003	2003	
	plants ha^{-1} × 10^3				g				pods plant^{-1}	
1	480	347	474	492	16.9	12.7	14.6	13.1	24	31
2	460	338	446	568	16.2	12.2	14.9	12.8	21	25
3	443	303	477	476	16.5	12.5	15.0	12.5	29	26
4	431	390	428	505	16.9	13.8	14.6	12.8	20	17
5	525	332	418	449	16.8	12.8	14.8	12.7	26	18
6	505	299	461	502	16.1	12.8	15.7	12.1	28	18
7	374	301	392	440	15.9	14.3	14.8	12.7	23	21
8	435	340	413	482	16.1	12.3	14.9	13.1	23	23
9	460	281	361	440	16.6	12.9	14.2	14.4	26	28
10	423	342	354	358	15.7	13.5	14.1	13.2	16	12
11	476	336	397	453	16.0	13.3	14.9	13.2	17	15
12	468	293	382	453	16.3	13.2	14.8	14.1	19	19
13	–†	263	325	331	15.4	13.5	14.6	14.1	19	18
14	–	288	325	377	15.4	12.6	14.9	13.6	19	20
15	–	319	387	476	15.7	13.3	14.6	13.3	20	17
16	493	326	479	574	16.0	12.6	14.9	13.0	28	27
17	431	281	365	486	16.1	12.8	14.8	13.1	27	27
18	456	254	490	456	16.4	14.9	14.7	12.9	25	23
19	456	322	489	538	16.2	13.5	15.5	12.7	22	17
20	415	209	435	397	15.3	14.2	14.0	12.8	28	23
21	484	226	446	381	16.0	14.0	15.2	14.2	24	14
22	517	287	487	486	16.8	12.9	15.1	12.7	24	24
Avg.	460	304	420	460	16.2	13.2	14.8	13.1	23	21
LSD		83				1.0			5	
ANOVA										
Year (Y)		***				***			NA‡	
Location (L)		***				***			**	
Y × L		***				***			NA	
Block (Y × L)		NS§				NS			NS	
Treatment (T)		***				NS			***	
Y × T		NS				***			NA	
L × T		***				***			***	
Y × L × T		***				***			NA	

** Significant at the $P = 0.01$ probability level.
*** Significant at the $P = 0.001$ probability level.
† Data not taken due to mowing error.
‡ NA = not applicable.
§ NS = not significant at the $P = 0.05$ probability level.

Economic analysis associated with each trt indicated the no-rye, early planted soybean control trt with herbicide applied once late (trt 16) resulted in the greatest economic return at each location each year; however at Waseca, certain other trts were just as good (Table 4). This was the lowest-costing trts as there was no cost associated with purchasing and planting rye seed and only one herbicide application. Across the two locations and 2 yr, the other two no-rye control trts (trts 17 and 22) also had high economic returns, but perhaps surprisingly, the two trts with rye managed by two herbicide applications or mowing followed by a herbicide on the third rye control date (trts 3 and 9, respectively) had comparable economic returns (Table 4).

The no-rye single herbicide application (trt 16) had the greatest economic return each year at each location, except at Waseca in 2002 when the no-rye, late-planted soybean trt (trt 22) was greatest (Table 4). Where weed populations were high, such as at Waseca both years (Table 6), trts with no secondary weed management with a herbicide (trts 4–6, 10–15, 19, and 21) resulted in lower economic returns. At Rosemount where weed pressure was low, however, when rye was mowed and then controlled with a herbicide later in the season (trts 8–9), returns were equal to the two-pass herbicide no-rye and rye trts (trts 1–3, 17, and 22). At Rosemount, lower yields as a result of the late planting contributed more to decreased returns than did rye management timing or method.

CONCLUSIONS

This study evaluated the influence of rye management method and timing on subsequent soybean production in the upper Midwest. Rye was planted following corn harvest at two locations in two separate years. Rye was mowed or terminated with a herbicide on several dates in May or June, and in some trts, a secondary mowing or herbicide application was applied. Soybean was no-till drilled into the rye, in some trts before it was managed with mowing or a herbicide. Rye biomass increased exponentially in May and accumulated over 20 kg N ha^{-1} by the end of the month at all locations. Rye regrowth was substantial when mowed early in May compared with later in the month. When mowing occurred near anthesis, very little regrowth occurred.

Mowing at earlier growth stages resulted in substantial rye regrowth, resulting in competition with soybean for light and moisture. Controlling rye early in the season with a herbicide limited the potential for soil water

Table 6. Dominate weed species population and aboveground biomass at the end of August at Waseca in 2002 and 2003.

	Weed population				Aboveground biomass			
	2002		2003		2002		2003	
Trt	Giant ragweed	Common ragweed	Common cocklebur	Giant foxtail	Giant ragweed	Common ragweed	Common cocklebur	Giant foxtail
	plants m^{-2}				g m^{-2}			
1	1.8	0.7	0.0	0.0	38.6	6.7	0.0	0.0
2	2.3	0.0	0.0	0.0	26.8	0.0	0.0	0.0
3	1.1	0.5	0.2	0.2	29.2	0.0	0.1	0.5
4	52.0	4.6	1.8	16.2	294.6	50.2	73.0	157.2
5	28.5	8.9	4.5	16.0	201.5	19.8	149.7	85.5
6	11.5	2.9	3.7	10.9	143.5	2.8	144.6	69.2
7	12.1	0.0	1.6	2.7	47.8	0.0	26.4	8.8
8	4.1	0.0	1.2	5.3	73.1	0.0	15.8	18.8
9	3.4	0.2	1.0	4.9	20.5	0.4	16.9	22.3
10	22.8	15.5	2.9	11.5	103.9	34.5	27.4	23.8
11	3.6	59.4	2.3	11.9	21.0	69.2	18.4	25.8
12	49.2	33.4	1.8	8.8	84.0	37.0	14.2	28.3
13	25.9	91.6	3.1	26.4	30.9	78.0	44.1	87.0
14	13.3	89.0	2.7	15.2	27.3	82.8	31.1	51.1
15	29.3	59.7	3.1	17.8	40.2	58.7	47.0	64.5
16	6.4	0.0	0.0	0.0	64.4	0.0	0.0	0.0
17	8.6	0.2	0.0	0.0	59.9	0.2	0.0	0.0
18	1.5	0.6	0.0	0.0	3.5	4.0	0.0	0.0
19	8.8	4.2	3.3	10.2	188.0	15.0	92.6	61.4
20	0.4	0.0	0.0	0.0	0.4	0.0	0.0	0.0
21	38.8	89.2	3.1	22.7	52.8	57.6	32.8	52.4
22	0.8	0.0	0.0	0.0	1.2	0.0	0.0	0.0
$P > F$	0.002	0.001	0.001	0.001	0.001	0.001	0.001	0.001

content to be reduced but did not allow time for much biomass and N accumulation. At the Waseca location where weed pressure was very high, rye did not adequately reduce weed populations, and weed pressure reduced soybean yields if not adequately controlled with a herbicide. At Rosemount, where weed pressure was low, the use of rye on certain trts had no negative impact on soybean yield or economic return. In such cases, rye can be used in the corn–soybean rotation with little crop interference, resulting in economic returns equal to conventional practices. However, the results from Waseca indicated rye does not adequately control the weeds GIRW, CORW, GIFT, and COCB when their populations are high, and rye should not be used as a stand-alone weed management tactic when these weed populations are high. The application of a herbicide late in the season for rye regrowth control and weed control dramatically improved soybean yield, making the use of rye in the cropping system comparable to conventional winter fallow systems, especially if incentive payments were made to achieve the environmental benefits a cover crop such as rye can provide.

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