Organically Managed No-Tillage Rye–Soybean Systems: Agronomic, Economic, and Environmental Assessment

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ABSTRACT

A major challenge that organic grain crop growers face is weed management. The use of a rye (*Secale cereale* L.) cover crop to facilitate no-tillage (NT) organic soybean [*Glycine max* (L.) Merr.] production may improve weed suppression and increase profitability. We conducted research in 2008 and 2009 to determine the effect of rye management (tilling, crimping, and mowing), soybean planting date (mid-May or early June), and soybean row width (76 or 19 cm), on soybean establishment, soil moisture, weed suppression, soybean yield, and profitability. Soybean establishment did not differ between tilled and NT treatments; and soil moisture measurements showed minimal risk of a drier soil profile in NT rye treatments. Rye mulch treatments effectively suppressed weeds, with 75% less weed biomass than in the tilled treatment by mid-July. However, by this time, NT soybean competed with rye regrowth, were deficient in Cu, and accumulated 22% as much dry matter (DM) and 28% as much N compared to the tilled treatment. Soybean row width and planting date within NT treatments impacted soybean productivity but not profitability, with few differences between mowed and crimped rye. Soybean yield was 24% less in the NT treatments than the tilled treatment, and profitability per hectare was 27% less. However, with fewer labor inputs, profitability per hour in NT rye treatments was 25% greater than in tilled soybean; in addition, predicted soil erosion was nearly 90% less. Although soybean yields were less in NT rye mulch systems, they represent economically viable alternatives for organic producers in the Upper Midwest.

Consumer demand for organically-produced food has risen steadily over the last decade, accounting for more than $21 billion in sales in 2008 (USDA-ERS et al., 2009). Consumers cite both beliefs that organic foods are healthier and that organic agriculture is better for the environment (Goldman and Clancy, 1991; Hartman Group, 1997). In the case of organic dairy, consumer demand is primarily driven by the preference for dairy produced without recombinant bovine growth hormone (DuPuis, 2000).

From 2000 to 2008, the number of certified organic farms increased 65% in the United States, and 130% in Wisconsin (USDA-ERS and Greene, 2009; USDA-NASS, 2010). Wisconsin is second in the United States in number of certified farms, roughly half of which are organic dairies (USDA-NASS, 2010). The rapid rise in organic dairy production in Wisconsin, 320% increase in the number of organic milk cows (*Bos taurus*) from 2000 to 2008, has led to a simultaneous increase in organic pasture and feed-grain production (USDA-ERS and Greene, 2009). A major challenge that organic grain crop growers face is managing weed communities using tillage and cultivation (Porter et al., 2003; Cavigelli et al., 2008; Posner et al., 2008), spurring interest in improving approaches to weed management (Walz, 1999).

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The use of a rye cover crop to facilitate NT organic soybean production may improve weed management and eliminate the need for tillage, as well as provide ecosystem services that include reduced soil erosion and runoff, increased soil organic matter and water infiltration, and trapping of excess N (Kaspar et al., 2001; Hartwig and Ammon, 2002; Ruffo et al., 2004).

Grower adoption of NT rye mulch systems has been limited in part due to uncertainty regarding the reliability of mechanical methods of managing the cover crop (Westgate et al., 2005), difficulty of soybean establishment in rye residue (Wagner-Riddle et al., 1994; Williams II et al., 2000; De Bruin et al., 2005), the inadequate efficacy of a rye mulch alone for weed suppression (De Bruin et al., 2005; Price et al., 2006), and the potential risk of competition between the rye cover crop and soybean for soil moisture and nutrients resulting in reduced yields and economic returns (Wagner-Riddle et al., 1994; De Bruin et al., 2005; Westgate et al., 2005). Nonetheless, many growers have expressed interest in using an organic NT rye–soybean system (Sooby et al., 2007) due to the perceived benefits of reduced labor and fuel inputs associated with NT farming, and reduced risk of soil erosion and increased soil organic matter over time. Recent estimates indicate that approximately one-third of the certified and exempt organic farms used NT or minimum-tillage practices in some manner (USDA-NASS, 2010).

No-tillage rye cover crop mulch systems have also been associated with reduced soybean DM accumulation and delayed development (Westgate et al., 2005), as well as reduced and delayed soybean canopy volume (Williams II et al., 2000). Most of the research on the effect of rye on NT soybean yields, however, has been done in conventional production systems. The results have been variable: ranging from increased yield

Abbreviations: DM, dry matter; GDU, growing degree units; NT, no-tillage; PD, planting date; R1, beginning bloom; R2, full bloom; R6, full seed; R8, full maturity; VC, unrolled unifoliate leaves.

Table 1. Rye and soybean management treatments for experiments conducted at the University of Wisconsin-Arlington Agricultural Research Station in 2008 and 2009.

Year	Treatment	Rye management		Soybean planting	Soybean row width	Soybean viable seeding rate
		implement	date	date	cm	seeds ha^{-1}
2008						
	Tilled	Chisel-disk	23 Apr.	21 May	76	511,500
	Mowed	Mowed	11 June	21 May	76	511,500
	Drilled-crimped	Crimped	11 June	21 May	19	625,200
	Drilled-mowed	Mowed	11 June	21 May	19	625,200
	Crimped-drilled-late	Crimped	11 June	17 June	19	568,300
	Mowed-drilled-late	Mowed	11 June	17 June	19	568,300
2009						
	Tilled	Chisel-disk	17 Apr.	18 May	76	511,500
	Mowed	Mowed	6 June	18 May	76	511,500
	Drilled-crimped	Crimped	6 June and 12 June	18 May	19	625,200
	Drilled-mowed	Mowed	6 June	18 May	19	625,200
	Crimped-drilled-late	Crimped	6 June and 12 June	6 June	19	625,200
	Mowed-drilled-late	Mowed	6 June	6 June	19	625,200

(Williams II et al., 2000; Price et al., 2006); to no effect (Moore et al., 1994; Wagner-Riddle et al., 1994; Ruffo et al., 2004); to decreased yield (Williams II et al., 2000; De Bruin et al., 2005; Westgate et al., 2005).

Additional research has identified techniques to improve rye management in these systems. Several studies have reported that regrowth from a rye cover crop is minimized if mechanical management occurs at anthesis or later, whether by using a mower (Wilkins and Bellinder, 1996) or a roller-crimper (a drum roller with blunt metal blades that is rolled over a standing cover crop to crimp and flatten stem tissue) (Ashford and Reeves, 2003; Mirsky et al., 2009). In contrast, Westgate et al. (2005) observed substantial regrowth from rye killed at anthesis with a stalk chopper.

Delaying soybean planting date until rye management has occurred is common, but may result in reduced yields. A combined analysis of many planting date experiments in the Midwest identified 30 May as the critical planting date after which soybean experiences a rapid decline in yield (Egli and Cornelius, 2009). Porter et al. (2005), working in Minnesota reported improved soybean establishment and weed management with a system of planting soybean in May into standing rye, followed by shredding the rye into mulch in June. This approach allowed for earlier planting of soybean before managing the rye at anthesis, avoidance of soybean seed–soil contact problems, and improved weed management, resulting in increased yields and economic returns.

No-tillage rye–soybean systems may also benefit from higher soybean populations or narrower soybean row width. Since NT rye–soybean systems are relying on the rye mulch and soybean competitive ability entirely for weed management, increasing the soybean density and decreasing the soybean row width could improve weed management and yields in these systems. Organic tilled soybean systems, on the other hand, rely on mechanical weed management and require wide soybean rows. Studies in Wisconsin and Michigan found that both higher soybean densities and narrower-row width (19 vs. 76 cm) resulted in increased soybean competitive ability, yield, and gross margins (Harder et al., 2007; Kelley and Sweeney, 2008).

Few researchers have compared organic tilled and organic NT rye–soybean systems. Our objectives were twofold: to better understand the risks associated with the use of winter rye cover crop in NT organic soybean production systems; and to optimize both soybean productivity and weed management in the organic NT rye system using a multitactic approach. Specifically, we conducted research to determine the effect of rye management (tilling, crimping, and mowing), soybean planting date (mid-May into standing rye or early June into the rye mulch), and soybean row width (76 or 19 cm) on soybean stand establishment, soil moisture availability, soybean, rye, and weed biomass, and soybean yield. Treatment effects on economic gross margins, labor and fuel inputs, soil loss, and soil quality were also predicted.

MATERIALS AND METHODS

Experimental Design and Field Procedures

Research was conducted at the University of Wisconsin Arlington Agricultural Research Station (UWAARS) (43°18’ N; 89°21’ W; 315 m above sea level) near Arlington, WI in 2008 and 2009. The soil type was a Plano silt loam (fine-silty, mixed, superactive, mesic Typic Argiudoll) with 4.7% organic matter and pH 6.7 in 2008, 3.6% organic matter and pH 6.0 in 2009, and excessively high levels of soil test P and K, all typical characteristics of prairie-derived soils of Wisconsin (Laboski et al., 2006; University of Wisconsin Soil Testing Laboratories, 2010). Research sites changed each year to place the study following corn silage and were managed organically but not certified organic. The experimental design was a randomized complete block with four replications of six treatments (Table 1). The tilled treatment represented a typical organic soybean production system, including the planting of a winter rye cover crop that was tilled several weeks before soybean planting. Winter cover crops are typically grown this way in organic tilled systems to help fulfill the USDA National Organic Program requirements. It is recommended to manage the rye this early to minimize negative effects on the subsequent soybean crop establishment (Oelke et al., 1990; Van Wychen Bennett et al., 2010). Since the rye had accumulated relatively little biomass before

[1] References to products in this publication are for your convenience and are not an endorsement or criticism of one product over similar products.

Table 2. Pre-plant and in-crop tillage practices for the tilled treatment in experiments conducted at the University of Wisconsin–Arlington Agricultural Research Station in 2008 and 2009.

Year	Pre-plant tillage			In-crop tillage		
	Chisel-disk	Disk	Seedbed preparation†	Tine weeding	Rotary hoeing	Interrow cultivation
	date					
2008	23 Apr.	2 May	21 May (2x)‡	28 May	–	24 June
	–	9 May	–	16 June (2x)	–	2 July
	–	–	–	–	–	15 July
2009	17 Apr.	12 May (2x)	18 May (3x)	22 May	1 June	26 June
	–	–	–	–	12 June	7 July
	–	–	–	–	18 June	–

† Soil finisher in 2008, field cultivator (2x) and cultipacker (1x) in 2009.

‡ '2x' and '3x' indicates two and three passes, respectively.

tillage it could be roughly equivalent to a no rye check. The other five treatments were NT rye cover crop treatments with varying factors of rye management, soybean planting date, and row width (seeding rate). Plot size was 9 m wide by 55 m long in 2008 (0.050 ha) and 9 m wide by 50 m long in 2009 (0.045 ha).

Winter rye variety 'Rymin' was planted in early October (5 Oct. 2007 and 10 Oct. 2008) at a rate of 180 kg ha^{-1} by a 3-m wide NT drill (Model 750, John Deere, Moline, IL[1]) with a depth of 2.5 cm and row width of 19 cm. The rye seed was certified organic in 2008, and was conventional (non-GMO) untreated in 2009. Rye in the tilled treatment was chisel-disked (4.6-m wide) to a depth of 15 cm in mid-April both years, at the second node growth stage (Feekes growth stage 7) in 2008 and at tillering (Feekes growth stage 4) in 2009 (Table 2) (Zadoks et al., 1974). The subsequent stale seedbed was lightly disked (3.7-m wide) for weed management, then prepared for soybean planting with a soil finisher (7.7-m wide) in 2008 or field cultivator (3.7-m wide) and cultipacker (4.6-m wide) (Table 2). Organic feed-grade soybean cultivars (Maturity Group I) 'Viking 0.1832' in 2008 and 'Blue River 16A7' in 2009 (due to unavailability of 'Viking 0.1832' in 2009) were treated with Cell-Tech SCI, an Organic Materials Review Institute approved (at the time) liquid inoculant (EMD Crop BioScience, Brookfield, WI[1]), and planted with a 4.6-m wide conservation-tillage planter (Model 1750 Max Emerge Plus, Conservation Tillage, John Deere, Moline, IL[1]) (76-cm row width) or 3-m wide NT drill (19-cm row width) at a depth of 3.8 cm. In the mowed, drilled-crimped, and drilled-mowed treatments (Table 1), soybean was planted on the same date as in the tilled treatment check, approximately 2 wk before crimping or mowing the rye. Rye in the five NT treatments was roller-crimped (4.6-m wide) (I and J Manufacturing, Gap, PA[1]) or sickle-bar mowed (2.1-m wide) in early June after the rye reached late anthesis (Feekes stage 10.5.1). Each year, shortly after the rye was crimped or mowed, soybean was drilled in the remaining two treatments (crimped-drilled-late and mowed-drilled-late) (Table 1).

Planting narrow row soybean at a higher seeding rate than that of wide row soybean is recommended and also typical in Wisconsin, so wide row soybean was planted at 511,500 seeds ha^{-1} and narrow row soybean was planted at 625,000 seeds ha^{-1} (Oplinger and Philbrook, 1992; Conley and Gaska, 2010). An error in 2008 resulted in a 9% lower seeding rate (568,300) in the NT rye late planted drilled treatments (Table 1). In 2009, all the seeding rates matched the protocol. It is hypothesized that this error did not have an important impact on yield, as previous research has shown that soybean yield was optimized in the seeding rate ranges of 556,000 to 680,000 seeds ha^{-1} in Wisconsin (Bertram and Pedersen, 2004).

The 4.6-m long roller-crimper was filled with water, for a total mass of 1360 kg. In 2009, the rye was crimped twice (on 6 and 12 June). The NT drill had cutting coulters, and both years was increased in mass by 800 kg to ensure uniform planting depth. The planter had cutting coulters and both years the row cleaners were removed to avoid clogging in the rye mulch. In the tilled treatment, flex-tine weeding (4.6-m wide), rotary hoeing (4.6-m wide), and interrow cultivation (4.6-m wide) were used for weed management as needed, typically two to three passes each, spaced about 1 wk apart from mid-May until soybean canopy closure in July (Table 2). Seedbed preparation and mechanical weed management in the tilled treatment was similar to the management of tilled organic soybean treatments in several studies conducted in the upper Midwest (Porter et al., 2003; Delate and Cambardella, 2004; Posner et al., 2008).

Data Collection

Weather data were measured at a meteorological station about 1.7 and 3.2 km from the research sites in 2007–2008 and 2008–2009, respectively (Wisconsin State Climatology Office, 2007–2009). Growing degree units (GDU) were calculated for rye using a base temperature of 1°C and optimum temperature of 18°C (Feyereisen et al., 2006). Growing degree units for soybean were calculated using a base temperature of 10°C and optimum temperature of 30°C (Zhang et al., 2001). Rye aboveground biomass was harvested, with a 2.5 cm cutting height, in four 0.1-m^2 quadrats per replicate before tillage (mid-April) and mowing or crimping (early June) treatments. Soil residue cover was estimated using the line-transect method in the end of June each year (Shelton and Jasa, 2009). Three counts per plot were taken with a 9.1-m line containing 30 points spaced 0.3 m apart, for a total of 90 points per plot. The lines were laid diagonally at a 45° angle across crop rows. Soybean stand density was determined by counting the number of soybean plants in 5.3 m of row in four subsamples per plot in treatments with 76-cm row width, and within a radius of 37 cm in four subsamples per plot in treatments with 19-cm row width. Soil moisture was measured before, and just after rye management in the tilled and crimped-drilled-late treatments at 0- to 6-, 20- to 26-, 38- to 44-, and 51- to 57-cm depths in four subsamples per plot using a capacitance soil moisture sensor (Delta-T Devices, Cambridge, UK[1]). Soil moisture was also measured weekly in each treatment after planting through mid-July, and biweekly thereafter until early September at 0- to 6- and 20- to 26-cm depths

Table 3. Effects of treatment (tillage and rye cover crop, rye termination method, soybean planting date, and soybean row width), sampling date, and their two-way interaction on soil moisture in models with repeated measures corresponding to the means presented in Fig. 1 and Fig. 2. Data sampled at the University of Wisconsin–Arlington Agricultural Research Station in 2008 and 2009.

	Fixed effects		
	Treatment	Sampling date	Treatment × sampling date interaction
		$P > F$	
Early-season soil moisture (Fig. 1)			
2008			
0–6 cm	***	***	***
20–26 cm	**	***	***
38–42 cm	**	***	***
51–57 cm	†	***	***
2009			
0–6 cm	***	***	**
20–26 cm	†	***	*
38–42 cm	**	*	**
51–57 cm	**	ns‡	***
Mid- to late-season soil moisture (Fig. 2)			
2008			
0–6 cm	***	***	***
20–26 cm	***	***	***
2009			
0–6 cm	***	***	***
20–26 cm	**	***	†

* Significant at the 0.05 probability level.

** Significant at the 0.01 probability level.

*** Significant at the 0.001 probability level.

† Significant at the 0.1 probability level.

‡ ns, nonsignificant at the 0.1 probability level.

in four subsamples per plot. In mid-July, rye tiller regrowth, soybean, and weed aboveground biomass was harvested by hand cutting at a height of 2.5 cm in four 0.25-m^2 quadrats per plot centered on the soybean rows, dried at 21°C in a forced air oven until constant mass was achieved, and weighed.

Soybean tissue nutrient status was measured at the R1 soybean stage (beginning bloom; Ritchie et al., 1997) each year (16 July 2008 and 14 July 2009) by collecting the youngest fully developed leaf from 25 plants per plot in the tilled and mowed treatments. Leaf samples were composited and analyzed for N, P, K, Ca, Mg, S, Zn, B, Mn, Fe, Cu, Al, and Na (University of Wisconsin Soil and Plant Analysis Laboratory, UW-SPAL, Madison) (Peters, 2010). On the same dates that leaf samples were collected, six soil cores (15.2-cm depth, 1.9 cm i.d.) per plot in the tilled and mowed treatments were composited and analyzed for Bray-extractable P, K, organic matter, and pH (UW-SPAL) using the methods of Peters (2010), and the results were interpreted according to the sufficiency guidelines of Laboski et al. (2006). In 2009, additional composite soil samples of three soil cores (30.5-cm depth; 1.9 cm i.d.) per plot were collected on 14 July in the tilled and mowed treatments and analyzed for NO_3–N concentration (UW-SPAL). At the R8 soybean growth stage (full maturity; Ritchie et al., 1997), grain yield was measured by machine harvest of the center 4.6 m (six rows in wide row treatments and 24 rows in narrow row treatments) of each plot and yields were adjusted to 13% moisture.

Gross margins (return to capital, labor, and management) were calculated using Agricultural Budget Calculation Software (Frank and Gregory, 2000). Input data included equipment type, size, and model for all field operations in each treatment, actual costs incurred by the research farm each year for organic rye seed, soybean seed, soybean inoculants, diesel fuel, and local market (South Central Wisconsin) price for pest scouting, input interest rates, and organic feed grade soybeans in November. Fuel use, labor inputs (although operator labor was not included as a variable cost), engine lubrication costs, and repair and maintenance of the machinery, were estimated by the Agricultural Budget Calculation Software based on field operations and equipment used in each treatment each year. Besides engine lubrication and repair and maintenance, machinery costs also included custom hauling of the harvested grain to market within 100 miles, based on Iowa custom rates (Edwards and Smith, 2008; Edwards et al., 2009). Depreciation was not included as a variable cost. The area under soybean production on a typical organic farm in Wisconsin, used in the interpretation of the economic analysis, was estimated at 18 ha. This is based on the total amount of certified organic soybean acreage and number of certified organic farms reported to be growing soybean in Wisconsin (USDA-NASS, 2010). The Revised Universal Soil Loss Eq. [2] model was used to predict treatment effects on soil loss and the soil conditioning index based on a run of 61 m, contours of 0.5%, and 1.0 and 4.5% slopes (USDA-ARS, 2003). The soil conditioning index is used by the NRCS to estimate whether conservation practices will result in increased or maintained soil organic matter over time, an indicator of changes in soil quality (USDA-NRCS, 2003).

Data Analysis

Analysis of variance was conducted using the MIXED procedure in SAS/STAT (SAS Institute, 2007) to test the effect of treatments on soybean establishment, soil moisture, soybean tissue nutrient concentration and uptake, rye regrowth, soybean and weed aboveground biomass, soybean yield, profitability, and costs. Data from each site-year were combined (with the exception of soil moisture and nutrient data) and site-year, block within site-year, and site-year by treatment were considered random effects. Soil moisture data were analyzed using repeated measures, with the block, block × treatment interaction, and block × sampling date interaction considered random. Model testing was used to determine that the null independent covariance model (where the within-subject error correlation is zero) fit best (Littell et al., 2006). Data are presented by sampling date since the sampling date × treatment interaction was significant in all cases (Table 3). Treatment effects on tissue nutrient concentration and uptake were determined within site-year, with block considered random. Nutrient data from each site-year were not combined since the results were different among site-years and also since the restricted maximum likelihood method of estimating variance components is unreliable when there is only one error degree of freedom (two site-years and two treatments) (SAS Institute, 2007). All data were tested for homogeneity of variance by examining residual vs. predicted plots and for normal distribution of variance using the UNIVARIATE procedure to examine quantile-quantile plots (Piepho, 2009; Onofri et al., 2010). Data were transformed if needed using the Box-Cox family of power transformations in the TRANSREG procedure

Table 4. Effects of tillage and rye cover crop, rye termination method, soybean planting date, and soybean row width on soybean density and establishment (stand density as percent of viable seeding rate) at the University of Wisconsin–Arlington Agricultural Research Station, combined from 8 July 2008 and 1 July 2009; and soybean, rye, and weed aboveground biomass combined from 15 July 2008 and 16 July 2009. Least squares means are presented.

Treatment	Soybean stand		Biomass		
	Density	Establishment	Soybean	Rye	Weed
	plants ha^{-1}	%	kg DM ha^{-1}		
Tilled (T1)	405,300	79	1918	0	26
Mowed (T2)	407,000	80	449	939	5
Drilled-crimped (T3)	505,600	81	565	604	7
Drilled-mowed (T4)	492,000	79	749	1212	5
Crimped-drilled-late (T5)	377,100	62	156	186	6
Mowed-drilled-late (T6)	329,900	54	174	345	10
Contrast†	$P > F$				
Tilled vs. NT rye	ns‡	ns	**	**	***
NT: wide vs. narrow width	ns	ns	ns	ns	ns
NT: early vs. late PD	§	*	**	*	ns
NT: mowed vs. crimped rye	ns	ns	ns	ns	ns
NT: PD × crimped/mowed rye¶	ns	ns	ns	ns	ns

* Significant at the 0.05 probability level.

** Significant at the 0.01 probability level.

*** Significant at the 0.001 probability level.

† NT, no-till rye; PD, planting date; Tilled vs. NT rye, T1 vs. T2, T3, T4, T5, and T6; NT: wide vs. narrow width, T2 vs. T4; NT: early vs. late PD, T3 and T4 vs. T5 and T6; NT: mowed vs. crimped rye, T4 and T6 vs. T3 and T5; NT: PD x crimped/mowed rye, T3 and T6 vs. T4 and T5.

‡ ns, nonsignificant at the 0.1 probability level.

§ Significant at the 0.1 probability level.

¶ Second-level interaction of planting date and rye management.

(Piepho, 2009). Rye biomass, and soybean tissue P, Ca, S, and B, were log-transformed. Rye regrowth and soybean biomass were fourth root transformed, and weed biomass was inverse fourth root transformed. Back transformed means are presented for ease of interpretation. Preplanned contrasts were made to compare tilled and NT treatments and then to compare rye and soybean management effects within the five NT treatments.

RESULTS

Weather

Growing seasons in each year for rye and soybean were characterized by temperatures below the long-term average (1985–2007) and variable precipitation (data not shown). During the rye growing season from 1 October to 30 May, cumulative GDU were 15 and 12% below the long-term average in 2007–2008 and 2008–2009, respectively. During the soybean growing season from 1 May to 30 September, the accumulation of GDU was 14 and 21% below the long-term average in 2008 and 2009, respectively. Precipitation during the rye growing season was similar to the long-term average (429 mm), but during the soybean growing season, 2008 was wetter (573 mm) and 2009 was drier (400 mm) than the long-term average (508 mm). Precipitation in June 2008 was almost threefold above average, which delayed field operations. However, May, August, and September of 2008 and July and September of 2009 were months with precipitation 43 to 61% below average (long-term average is 95 mm in May, 111 mm in June, 100 mm in July, 104 mm in August, and 98 mm in September).

Rye Biomass and Soil Cover

Rye aboveground DM in mid-April of 2008 was 1.6 Mg DM ha^{-1} in the tilled treatment, and averaged 10.8 Mg DM ha^{-1} in the mowed and crimped no-tillage treatments by early June ($P < 0.001$). In 2009, aboveground biomass was 0.4 Mg DM ha^{-1} in the tilled treatment (mid-April) and averaged 4.3 Mg DM ha^{-1} in the NT treatments (early June) ($P < 0.001$). Both years, soil cover in late June was greater in the rye treatments than in the tilled treatment, where soil cover consisted mostly of corn residue from the previous year. In 2008, soil cover provided by the rye mulch was 98% compared to 13% in the tilled treatment ($P < 0.001$), and in 2009 soil cover in the NT rye treatments was 99 vs. 6% in the tilled treatment ($P < 0.001$).

Soybean Stand Density and Establishment

Soybean density and establishment (stand density as a percent of viable seeding rate) did not differ between tilled and NT treatments, suggesting that rye had little adverse effect on soybean emergence (Table 4). However, within the no-tillage drilled treatments, soybean establishment was affected by planting date. Establishment in treatments planted before rye crimping or mowing (drilled-crimped and drilled-mowed) averaged 80%, whereas establishment averaged just 58% in treatments in which planting was delayed until after crimping or mowing (crimped-drilled-late and mowed-drilled-late). Soybean establishment was not affected by rye management (crimped or mowed) or row width (wide or narrow).

Mid-Season Aboveground Biomass

Both soybean and weed biomass were greater in the tilled treatment than in the NT treatments, while rye regrowth was, as expected, lower (Table 4). Both soybean biomass and rye regrowth were greater in early- than late-planted soybean, but were not affected by soybean row-width or rye management. Although weed biomass was several-fold greater in tilled than NT rye treatments, weed suppression was not affected by other

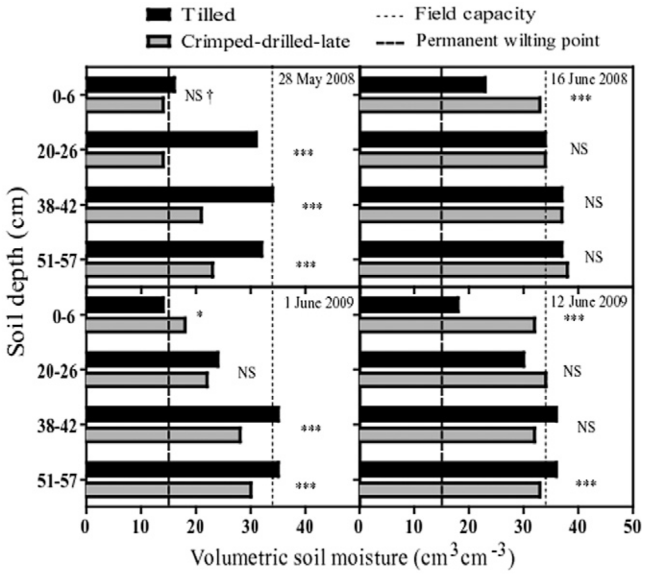

Fig. 1. Least squares mean early-season volumetric soil moisture content at the 0- to 57-cm depths for tilled and crimped-drilled-late treatments on several sampling dates in 2008 and 2009. *F* tests for differences between treatments within each sampling date and depth are presented. *Significant at the 0.05 probability level. ***Significant at the 0.001 probability level. †NS, nonsignificant at the 0.1 probability level.

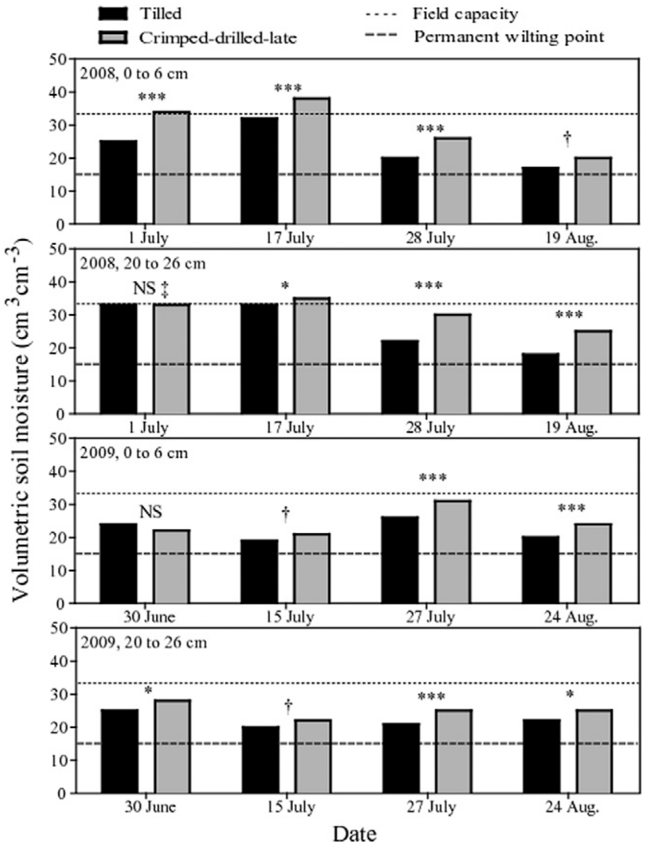

Fig. 2. Least squares mean volumetric soil moisture content on several sampling dates at the 0- to 6-cm depth in 2008; 20- to 26-cm depth in 2008; 0- to 6-cm depth in 2009; and 20- to 26-cm depth in 2009. *F* tests for differences between treatments within each year, depth, and sampling date are presented. *Significant at the 0.05 probability level. ***Significant at the 0.001 probability level. †Significant at the 0.1 probability level. ‡NS, nonsignificant at the 0.1 probability level.

treatment factors. Dominant weed species in the tilled treatment were common lambsquarters (*Chenopodium album* L.), velvetleaf (*Abutilon theophrasti* Medik.), and redroot pigweed (*Amaranthus retroflexus* L.) (data not shown). Dominant weed species in the NT treatments were common lambsquarters, prostrate knotweed (*Polygonum aviculare* L.), and white clover (*Trifolium repens* L.).

Soil Moisture

Early-season soil moisture before and after rye management in 2008 and 2009 showed little risk of a drier seedbed during soybean planting in the NT rye treatments relative to the tilled treatment, and deficits lower in the soil profile were recharged by mid-June (Fig. 1). Near the time of soybean planting and before rye management on 28 May 2008 and 1 June 2009, moisture was close to the permanent wilting point (within 1–3 cm^3 cm^{-3}) in both tilled and NT rye (crimped-drilled-late) treatments at shallow depths (0–6 cm), even though soil moisture in the NT rye treatment was greater than in the tilled treatment in 2009. At lower soil depths (20–26, 38–42, and 51–57 cm) soil moisture was generally less in the NT rye treatment than in the tilled treatment, which was near field capacity. After rye termination on 16 June 2008 and 12 June 2009, both treatments were near field capacity at all soil depths, except the tilled treatment which remained 3 to 8 cm^3 cm^{-3} above the permanent wilting point at the 0- to 6-cm depth. At all of the sampling dates between late June and late August, soil moisture at 0- to 6- and 20- to 26-cm depths in the NT rye treatment was either greater or not different compared to the tilled treatment (Fig. 2).

Soybean Tissue Nutrient Concentration and Uptake

Tissue nutrient concentrations at the R1 soybean growth stage indicated that P, K, Mg, Zn, and Fe were consistently sufficient or high in both tilled and NT mowed treatments (Table 5). Copper concentrations were consistently deficient in the NT mowed treatment, but occurred at sufficient amounts in the tilled treatment. Nitrogen concentrations in 2008 were also deficient in the NT mowed treatment, but not in the tilled treatment. In 2009, N concentrations were deficient in both treatments. Sulfur concentrations were deficient in both treatments in each year, as well as B and Mn concentrations in 2008. Although soil nutrient concentrations were similar among treatments (data not shown), soybean uptake of N, P, and K was several-fold greater in the tilled treatment than in the no-tillage mowed rye treatment both years (Table 5).

Soybean Productivity and Profitability

Soybean yield across years was 32% greater in the tilled treatment than NT rye treatments (Table 6). Among NT rye treatments, yield was 21% greater for narrow- than wide-row width, but yield was not affected by planting date or rye management. Despite 9% greater variable costs in the tilled treatment, it was also 36% more profitable per hectare than the NT rye treatments due to the greater yield and the high feed-grade organic soybean prices in 2008 (0.77 U.S.$ kg^{-1}) and 2009 (0.64 U.S.$ kg^{-1}) (Table 7). Narrow row width in the NT rye treatments was associated with 11% greater variable costs due to increased seed costs compared to wide row width, but was not associated with a lower return since yield was also greater in the NT soybean with narrow row width.

Table 5. Effects of tillage and rye cover crop on soybean tissue nutrient concentration and uptake at the soybean R1 soybean stage (beginning bloom; Ritchie et al., 1997) at the University of Wisconsin–Arlington Agricultural Research Station on 16 July 2008 and 14 July 2009. Least squares means are presented.

	Treatment					
	Tilled		No-till rye mowed		*F* test	
	2008	2009	2008	2009	2008	2009
	Value (qualifier†)				*P* > *F*	
	Tissue nutrient concentration					
Macronutrients						
N, g kg^{-1}	49 (S)	40 (L)	41 (L)	40 (L)	**	ns‡
P, g kg^{-1}	5.9 (S)	6.0 (S)	4.5 (S)	5.0 (S)	§	***
K, g kg^{-1}	32 (S)	25 (S)	33 (H)	25 (S)	ns	ns
Ca, g kg^{-1}	6.2 (L)	8.6 (S)	9.5 (S)	9.9 (S)	ns	**
Mg, g kg^{-1}	3.5 (S)	4.6 (S)	4.5 (S)	5.4 (S)	*	*
S, g kg^{-1}	2.6 (L)	2.6 (L)	2.4 (L)	2.3 (L)	ns	*
Micronutrients						
Zn, mg kg^{-1}	55 (S)	45 (S)	36 (S)	34 (S)	*	***
B, mg kg^{-1}	23 (L)	46 (S)	23 (L)	44 (S)	ns	ns
Mn, mg kg^{-1}	49 (L)	61 (S)	44 (L)	64 (S)	§	ns
Fe, mg kg^{-1}	361 (H)	78 (S)	112 (S)	64 (S)	ns	*
Cu, mg kg^{-1}	7.1 (S)	6.8 (S)	5.5 (L)	4.9 (L)	*	**
	Tissue nutrient uptake, kg ha^{-1}					
Macronutrients						
N	54	53	17	13	*	***
P	6.5	8.0	2.0	1.7	*	***
K	35	33	15	8.6	§	***

* Significant at the 0.05 probability level.

** Significant at the 0.01 probability level.

*** Significant at the 0.001 probability level.

† L, low; S, sufficient; H, high; VH, very high; EH, excessively high; according to the Soil and Plant Analysis Laboratory recommendations (Peters, 2010) and the University of Wisconsin Extension publication A2809 (Laboski et al., 2006).

‡ ns, nonsignificant at the 0.1 probability level.

§ Significant at the 0.1 probability level.

Variable costs and profitability were not affected by the other rye or soybean management factors among NT treatments.

Labor, Fuel Use, and Soil Loss

The NT rye treatments required less labor and fuel than the tilled treatment, due to fewer implement passes for tillage and weed management (Table 7). Estimated labor inputs (Agricultural Budget Calculation Software) were 46% lower in the NT (3.4 h ha^{-1}) than the tilled treatment (6.2 h ha^{-1}). Estimated diesel fuel use in the NT treatment was 50 L ha^{-1}, 42% less than the 90 L ha^{-1} in the tilled treatment.

Predicted soil loss (Revised Universal Soil Loss Eq. [2]) was several-fold greater in tilled rye than in NT rye treatments for both 1.0 and 4.5% slopes. Soil loss in NT rye, 1.5 Mg ha^{-1} on a 1.0% slope and 5.6 Mg ha^{-1} on a 4.5% slope, was less than the soil loss tolerance to maintain the soil as a productive resource (11.0 Mg ha^{-1}) in each scenario. In the tilled treatment, soil loss of 10.9 Mg ha^{-1} on a 1.0% slope, was slightly less than the soil loss tolerance, and on a 4.5% slope, soil loss of 49.3 Mg ha^{-1} was much greater than the soil loss tolerance. Predicted changes in soil organic matter (soil conditioning index, on a scale of –2 to +2), were positive in NT rye treatments (+0.4 on 1.0% slope and +0.3 on 4.5% slope) and negative in the tilled rye treatment for both slope grades, (–0.9 on 1.0% slope and > –2.0 on 4.5% slope).

Table 6. Effects of tillage and rye cover crop, rye termination method, soybean planting date, and soybean row width on soybean grain yield, variable costs, and return at the University of Wisconsin–Arlington Agricultural Research Station in 2008 and 2009. Least squares means are presented.

Treatment	Soybean grain yield	Variable costs†	Return‡
	kg ha^{-1}	U.S. $ ha^{-1}	
Tilled (T1)	3618	395	2162
Mowed (T2)	2505	340	1442
Drilled-crimped (T3)	2885	369	1687
Drilled-mowed (T4)	2944	376	1726
Crimped-drilled-late (T5)	2751	362	1598
Mowed-drilled-late (T6)	2599	366	1469
Contrast§	*P* > *F*		
Tilled vs. NT rye	**	**	**
NT: wide vs. narrow width	¶	*	ns#
NT: early vs. late PD	ns	ns	ns
NT: mowed vs. crimped rye	ns	ns	ns
NT: PD × crimped/mowed rye††	ns	ns	ns

* Significant at the 0.05 probability level.

** Significant at the 0.01 probability level.

*** Significant at the 0.001 probability level.

† Variable costs represent production costs (inputs, machinery, and repair and maintenance).

‡ Economic return to land, capital, and family labor.

§ NT, no-till; PD, planting date; Tilled vs. NT rye, T1 vs. T2, T3, T4, T5, and T6; NT: wide vs. narrow width, T2 vs. T4; NT: early vs. late PD, T3 and T4 vs. T5 and T6; NT: mowed vs. crimped rye, T4 and T6 vs. T3 and T5; NT: PD × crimped/mowed rye, T3 and T6 vs. T4 and T5.

¶ Significant at the 0.1 probability level.

\# ns indicates not significant.

†† Second-level interaction of planting date and rye management.

DISCUSSION

Rye Aboveground Biomass

In the NT rye treatments each year, rye biomass exceeded the minimum (3.4 Mg DM ha^{-1}) considered necessary for effective weed suppression (Doll and Mueller, 2005). Greater rye biomass in 2008 was likely due to more timely precipitation and somewhat warmer spring temperatures as well as greater soil fertility than in 2009 (data not shown). Both years the soil cover provided by the NT rye mulch was above the minimum of 97% identified by Teasdale et al. (1991) as necessary to reduce weed density by 75%.

Soybean Stand Density and Establishment

Soybean stand establishment was not affected by the presence of rye mulch in the early-planted NT rye treatments, the method of rye management, or soybean row width, but was lower in the later-planted NT rye treatments (Table 4). The lack of difference between the tilled and early-planted NT rye treatments indicates that rye did not have an adverse effect on soybean emergence, either due to allelopathy or soil moisture depletion. Row width also had no effect on establishment, indicating that the conservation planter and NT drill were equally effective under the high residue conditions. Soybean establishment was reduced in the late-planted NT rye treatments compared to soybean planted in May before rye management. Achieving good seed-soil contact in the late-planted NT rye treatments was particularly difficult due to the high amount of rye residue and wet field conditions in the spring of 2008. This difficulty in establishing NT soybean into a rye mulch has been observed widely in previous literature

Table 7. Effects of tillage and rye cover crop, rye termination method, soybean planting date, and soybean row width on variable costs, gross value of production, and labor inputs, at the University of Wisconsin–Arlington Agricultural Research Station in 2008 and 2009. Values estimated by the Agricultural Budget Calculation Software (Frank and Gregory, 2000).

Treatment	Variable costs							Gross value of production‡	Labor inputs¶
	Soybean seed†	Rye seed†	Soybean inoculant†	Pest scouting‡	Fuel†	Machinery costs§	Interest on input expenses‡		
	U.S. $ ha^{-1}								h ha^{-1}
Tilled	111	88	5	12	69	86	22	2557	6.2
Mowed	111	88	5	12	39	64	19	1782	3.5
Drilled-crimped	135	88	5	12	39	68	21	2056	3.1
Drilled-mowed	135	88	5	12	39	67	21	2102	3.5
Crimped-drilled-late	130	88	5	12	43	71	20	1960	3.1
Mowed-drilled-late	130	88	5	12	43	67	21	1835	3.5

† Source was actual costs incurred (U.S.$): 2008 soybean, $1 kg^{-1}; 2009 soybean, $1.5 kg^{-1}; 2008 rye, $0.4 kg^{-1}; 2009 rye, $0.5 kg^{-1}; 2008 soybean inoculant, $4 ha^{-1}; 2009 soybean inoculant, $7 ha^{-1}; 2008 diesel fuel, $0.9 L^{-1}; 2009 diesel fuel, $0.6 L^{-1}.

‡ Source was local (South Central Wisconsin) rate (U.S.$): pest scouting, $12 ha^{-1}; interest on input expenses, 6%; 2008 soybean price, $0.77 kg^{-1}; 2009 soybean price, $0.64 kg^{-1}.

§ Source was combination of Iowa custom rates for hauling grain to market within 100 miles, U.S. $0.011 kg^{-1} soybean both years (Edwards and Smith, 2008; Edwards et al., 2009); and software estimates of engine lubrication, repair, and maintenance costs based on actual field operations and equipment used.

¶ Source: estimated by software based on actual field operations and equipment used.

(Wagner-Riddle et al., 1994; De Bruin et al., 2005; Westgate et al., 2005). Confirming what Porter et al. (2005) reported, problems establishing soybean in rye residue was avoided by planting earlier into standing rye before rye management. Additionally, no loss of stand (compared to the tilled treatment) was observed due to crimping or mowing over the soybean seedlings in the early-planted NT rye treatments, even though rye management took place three wk after soybean planting. Soybean establishment rates observed in this study were greater than those observed in transitional organic tilled soybean treatments in Iowa (Delate and Cambardella, 2004).

Mid-Season Aboveground Biomass

Reduced soybean aboveground biomass (Table 4) in the NT rye treatments compared to the tilled treatment may have been due in part to the cooler (data not shown) and wetter soils (Fig. 2). This would be consistent with the reduced biomass accumulation in NT rye treatments compared to no-rye checks observed by Westgate et al. (2005). Another potential cause of the reduced soybean biomass was the substantial rye regrowth in the NT rye treatments (Table 4). Tiller regrowth occurred both years despite waiting until late anthesis to crimp or mow the rye, consistent with results of Westgate et al. (2005) for Rymin rye. The rye regrowth most likely did not compete with soybean for moisture (Fig. 1 and 2), but may have reduced light and nutrient availability to soybean. Rye regrowth in the NT rye treatments in mid-July accounted for the largest portion of aboveground biomass, exceeding that of soybean and weeds (Table 4). The majority of the weed community and the soybean crop are summer annuals growing rapidly and competing for resources. In contrast, rye as a winter annual was at advanced stages of its life cycle and therefore may not have been as competitive for resources.

Weed management was more effective in the NT rye treatments than in the tilled treatment, with an average of only 25% as much aboveground biomass across years (Table 4). The long-term effects on weed communities of a NT rye mulch compared to mechanical weed management is uncertain, as long-term research in conventional systems has found that weed management is both more effective in NT systems (Murphy et al., 2006) and less effective compared to tilled systems (Sosnoskie et al., 2006; Légère et al., 2008). One tactic employed to optimize soybean growth and competitiveness with weeds, an earlier date of soybean planting, did increase soybean aboveground biomass in the NT rye treatments, but did not impact weed biomas.

Soil Moisture

In both years, soil moisture differences between tilled and NT rye treatments were not of the magnitude such that soybean germination or establishment would have been expected to be affected (Fig. 1). Moisture was lower under the standing rye cover crop in late May than where tillage had killed the rye in April, except at the surface (0–6 cm) where both treatments were near the permanent wilting point. Following management of the rye cover crop in June, more soil water was available in the NT rye treatments than in the tilled treatment at the surface soil depth (0–6 cm), where the majority of soybean root biomass likely occurred (Mitchell and Russell, 1971; Mayaki et al., 1976). Precipitation in the first 3 wk of June (28 cm in 2008 and 7 cm in 2009) was sufficient both years to replenish the soil moisture through 57 cm (Fig. 1), a finding similar to that of Wagner-Riddle et al. (1994), Williams II et al. (2000), and Westgate et al. (2005). A Plano silt loam soil requires 1.9 cm of water to recharge the upper 10 cm of the soil profile from permanent wilting point to field capacity (USDA-NRCS, 2008). An analysis of the previous 30 yr of weather data (1978–2007) indicates that the probability of accumulated rainfall of 1.9 cm or more in the first 2 wk of June is 83%, and the probability of twice that amount, 3.8 cm, accumulating in that same time period is 53%. Our results suggest little risk of rye competition with soybean for soil moisture in South Central Wisconsin, as soil water deficits at depths deeper than 6 cm did not last into mid-June.

Late July and August, corresponding approximately to the soybean stages R2 (full bloom; Ritchie et al., 1997) through R6 (full seed), is the time period when moisture demand by soybean is the greatest (Peters and Johnson, 1960; Pedersen, 2004). At this time, available soil water was greater or not different in the NT rye treatment (crimped-drilled-late) compared to the tilled treatment (Fig. 2). Observations of greater soil moisture in the NT rye treatment may have been due to moisture conservation by the cover crop mulch (Munawar et al., 1990). An additional explanation for the greater moisture in the NT treatments was that moisture use by soybean was reduced since soybean biomass was less in the NT rye treatments compared to the tilled treatment (Table 4), similar to observations by Westgate et al. (2005).

Soybean Tissue Nutrient Concentration and Uptake

Deficiency of Cu and N (2008 only) in soybean tissue occurred in the NT rye treatment but not in the tilled treatment (Table 5). Copper is a micronutrient used in photosynthesis, protein and carbohydrate metabolism, and potentially binds to organic matter in soil or manure and plant residue, rendering it unavailable for uptake by plants (Marschner, 1995; Walker et al., 2003). The slowly decomposing rye cover crop may have bonded with available Cu. Visual symptoms of N deficiency were observed both years only in the NT rye treatments from the VC soybean stage (unrolled unifoliate leaves; Ritchie et al., 1997) in June through the R2 stage in August; however, symptoms were more pronounced in 2008 than 2009. Soybean N uptake in NT rye treatments was 80% less than in the tilled treatment both years. The cooler (data not shown) and wetter soils (Fig. 2) in the NT rye treatments may also have played a role in nutrient concentrations and uptake.

Reduced uptake of N in soybean aboveground biomass has been associated with reduced grain yield across many studies (Salvagiotti et al., 2008). Rye mulch and regrowth likely had sequestered a substantial amount of N (Ruffo and Bollero, 2003; Ruffo et al., 2004; Parkin et al., 2006). Rye as a cover crop has been associated with increased N immobilization and reduced N mineralization (Ruffo and Bollero, 2003; Parkin et al., 2006). In a greenhouse study, Heckman and Kluchinski (1995) found that rye residue amendments lead to N immobilization and deficiency, increased reliance on N fixed by rhizobia, and reduced soybean biomass. Increased soybean nodulation in NT rye treatments compared to conventional tillage was observed by Wagner-Riddle et al. (1994). In our study, mid-summer (14 July 2009) soil NO_3–N concentrations (0–30 cm) indicated that nitrate levels were low (6.6 mg kg^{-1}), but not different between treatments. Speculation on the long-term effects of NT rye treatments on N dynamics is difficult since the NT rye-soybean phase may be part of a NT rotation, or may be one NT phase in an otherwise tilled system. The immediate effects of a NT rye cover crop presented here would also be modified by the frequency of this phase in the overall organic rotation.

Soybean Productivity and Profitability

The 24% lower soybean yields observed in the NT rye treatments compared to the tilled treatment (Table 6), were potentially due to competition from the rye regrowth (Table 4), wetter (Fig. 2) and cooler (data not shown) soils, lower soybean tissue Cu concentration, and reduced nutrient uptake (Table 5). Other factors which were not measured in this study, such as increased N immobilization or reduced N mineralization, increased soybean nodulation, or allelopathic compounds released from the rye, may have also affected soybean productivity. These factors may have interacted and cumulatively reduced yield. DeBruin et al. (2005) also observed reduced soybean yield in NT rye treatments compared to no rye. Soybean grain yield was greater in narrow- than wide-row width NT rye treatments, but yield was not affected by rye management method (crimping or mowing) or soybean planting date (Table 6). A conventional study in Wisconsin also found that across several soybean seeding rates, narrow-row soybean yielded greater than wide-row soybean (Bertram and Pedersen, 2004). Soybean grain yield observed in our study was within the range of soybean grain yield reported in other organic studies in the upper Midwest (Porter et al., 2003; Delate and Cambardella, 2004; Posner et al., 2008).

Returns to labor, capital, and management in the NT rye treatments were 27% less than in the tilled treatment, despite lower variable costs (Table 6). None of the other rye or soybean management factors in the NT rye treatments in this trial affected economic return, suggesting that organic farmers have options in rye management (crimping or mowing) and can plant before or after rye management. Depending on the local weather conditions in late May and June, a grower can time soybean planting over a 3 wk period to avoid droughty or very wet conditions. The sickle-bar mower may be preferable to growers since it cost half as much as the roller-crimper.

Labor, Fuel Use, and Soil Loss

Labor and fuel inputs were reduced by nearly 50% in the NT rye treatments compared to the tilled treatment (Table 7). Although profitability per hectare was greater in the tilled treatment, since the NT rye treatments required significantly less labor, return per hour of labor was actually 25% greater in the NT rye system. For 18 ha of soybean, estimated as typical production area for an organic farm in Wisconsin, the total return for the tilled treatment would be \$38,920, requiring 112 h; and \$28,520 averaged across the NT rye treatments, requiring 60 h. The NT rye treatments would save 51 h of labor in spring and 720 L of diesel fuel. Reduced labor inputs associated with the NT rye treatments could increase a grower's quality of life, free their time to spend on a separate enterprise on their farm, or allow the grower to expand soybean hectarage. If a grower used NT rye management and chose to expand their soybean hectarage, with the additional 51 h they could grow 15 more ha of soybean, gaining an additional return of \$24,200, and bringing their total return for soybean to \$52,700. Other benefits to the NT rye management include the 86 to 89% reduction in predicted soil loss by the rye mulch, and predicted increase in organic matter levels under rye, consistent with the findings of related research (Kaspar et al., 2001; Villamil et al., 2006).

CONCLUSION

Organic NT rye–soybean treatments were associated with greater weed suppression, less soil loss and greater soil organic matter accumulation, and lower labor and fuel inputs than a tillage-intensive approach to organic soybean production. Although these potentially long-term benefits were offset by 24% less soybean yield and 27% less profit per hectare, profit per hour of labor input was 25% greater in the NT rye systems. The rye mulch, NT soybean treatments appear to be economically viable alternatives to the tillage-intensive approach; they are particularly attractive to organic growers due to reduced labor inputs, and positive impact on long-term soil quality.

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