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Reduced-Tillage Organic Corn Production in a Hairy Vetch Cover Crop

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ABSTRACT

There is interest in developing no-tillage systems for organic farming; however, potential limitations include the inability to control weeds and to provide sufficient crop available N. A 3-yr field experiment was conducted on organically certified land to explore roller-crimper technology for terminating a hairy vetch (*Vicia villosa* Roth) cover crop in a reduced-tillage compared to a disk-tillage organic corn (*Zea mays* L.) production system in Maryland. Within this tillage comparison, factors including the corn planting date and post-plant cultivation were examined for optimizing reduced-tillage organic corn production. Corn yield in roll-killed hairy vetch treatments where corn was planted by mid-June and that received high-residue cultivation was similar or higher than the best treatments with disk-killed hairy vetch. Delayed corn planting dates had little impact on corn yield in either disk- or roll-killed treatments, a result consistent with the similarity in weed biomass after cultivation, fertility, moisture, and radiation across planting dates. In 2 yr with supplemented weed populations, weed biomass was the major driver determining corn yield, which was reduced by 53 to 68% relative to weed-free control plots in the absence of post-plant cultivation, and by 21 to 28% with post-plant cultivation. In a year with low, natural weed populations, weeds had no significant influence on yield. These results demonstrate that organic corn production in a reduced-tillage roll-killed cover crop system can provide similar yields to those in a traditional tillage-based system, but also highlight the importance of maintaining low weed populations to optimize corn yield.

Acreage of organic farms and demand for organic products has increased in recent years (Dimitri and Oberholtzer, 2009; Greene and Slattery, 2010). Corn is one of the most challenging crops to grow organically because fertilizer and herbicide inputs, which are heavily relied on in conventional agriculture, are not permitted (Smith and Gross, 2006; Cavigelli et al., 2008; Posner et al., 2008). Because of the inability to use these inputs in organic agriculture, the overall system for growing corn must be designed to reliably manage fertility and weed populations. This requires the reevaluation of such basic agronomic practices as planting date and tillage for integration into an optimum organic production system.

Corn planting date has been well researched for conventional systems. When water and N are not limiting and after spring soil temperature has warmed sufficiently, corn yield usually declines when planting is delayed, although the magnitude of this effect depends on location and cultivar (Anapalli et al., 2005). In Kansas, delayed planting from early April to June resulted in a yield reduction, but the degree of yield reduction was less in a low-stress than a full-season moisture stress environment (Sindelar et al., 2010). In Pennsylvania, corn yield is estimated to decline by 25 kg ha^{-1} for every day planting is delayed beyond the recommended planting window in early May (Penn State Coop. Ext., 2011). However, this general approach to planting date may not necessarily apply to organic production because there are additional management trade-offs in organic systems resulting from reliance on biologically based fertility and weed management. When a legume cover crop such as hairy vetch is used as the primary N source for corn, delayed planting may provide more cover crop biomass production, thereby resulting in higher N content and greater available N for a succeeding corn crop (Cook et al., 2010; Mischler et al., 2010). In Maryland (Clark et al., 1994) and North Carolina (Wagger, 1989), corn planted into a hairy vetch cover crop without N fertilizer yielded higher when planted in May than April, a result that corresponded with the substantial gain in N content of hairy vetch during the period between kill dates.

Delayed planting could also improve weed control and reduce the competitive effect of weeds. In Wisconsin, mechanical weed control without herbicides provided better weed control when corn planting date was delayed (Mulder and Doll, 1994). In Illinois, delayed planting date reduced weed biomass, the magnitude of sweet corn yield loss caused by weeds, and the critical period for weed control (Williams, 2006, 2009). This result was explained by differential photosynthetic and photoperiodic responses between corn and weeds that were exploited by late planting dates. Also, because corn is more competitive with weeds in a high N environment (Evans et al., 2003a, 2003b), the accumulation of greater vetch N by delayed planting could enhance corn competitiveness with weeds.

There is much interest in developing no-tillage organic systems that would combine the soil protecting capacity of conventional no-tillage systems with the inherent soil building capacity of organic systems. No-till systems reduce soil and nutrient losses from agricultural fields and enhance soil organic carbon,

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aggregate stability, rainfall infiltration, and microbial activity compared with tillage-based systems (Doran, 1980; Angers et al., 1993; Beare et al., 1994; Angers and Eriksen-Hamel, 2008; Reicosky et al., 2011). Many of these benefits can be enhanced with cover crops as noted by Sainju et al. (2002) and Teasdale et al. (2007), who found greater soil C and N concentrations after several years of incorporating cover crops into no-till systems. Villamil et al. (2008) found lower soil bulk density and higher wet aggregate stability and soil organic matter content in no-till rotations with than without winter cover crops.

Inability to control weeds and to provide sufficient plant-available N are potential limitations of using conservation tillage practices in organic farming (Peigné et al., 2007). These problems were confirmed in long-term studies including no-till organic systems in Pennsylvania (Drinkwater et al., 2000) and a conservation tillage organic system in Maryland (Teasdale et al., 2007), where a combination of weed competition and low N availability from surface cover crop residue contributed to low corn yields. It seems clear that integration of weed-suppressive and fertility-enhancing cover crops with timely management will be required for development of a viable conservation tillage organic system.

The advent of roller-crimper technology provides a new approach to managing cover crops that has promise for achieving successful reduced-tillage organic systems. The most frequently used roller-crimper is composed of a 41 to 51 cm diameter steel cylinder with metal slats arranged in a chevron pattern to reduce vibration (Kornecki et al., 2006; The Rodale Institute, 2011). Sufficient pressure is focused on the blades during rolling operations to crush cover crop tissue and it can be operated at a speed that will accommodate use on typical sized mid-Atlantic grain farms. The roller-crimper has been tested in corn (Mischler et al., 2010), soybean [*Glycine max* (L.) Merr.] (Davis, 2010; Bernstein et al., 2011; Mirsky et al., 2011; Smith et al., 2011), and wheat (*Triticum aestivum* L.) (Vaisman et al., 2011) with mixed success. To date, roller-crimpers have been most successful when used to kill a rye cover crop before planting soybean, with equivalent yields having been achieved between rolled and chemically treated or weed-free controls (Davis, 2010; Smith et al., 2011). When soybean yield losses occurred in these experiments, it was the result of poor weed suppression due to low cover crop mulch biomass or poor crop populations due to planting difficulties into thick cover crop residue. In corn and wheat roll-killed systems, crop yield was impacted by regrowth of the cover crop (Hoffman et al., 1993), weed competition (Hoffman et al., 1993; Mischler et al., 2010), loss of crop population due to planter problems or insect pressure (Mischler et al., 2010), or reduced soil N (Vaisman et al., 2011).

Many of these limitations to the roller-based system could be addressed by optimizing the timing of operations. This research was conducted to evaluate the use of a roller-crimper for terminating a hairy vetch cover crop for organic corn production in comparison to a typical tillage-based organic production system across three dates ranging from a typical corn planting date for the area in early May to a late date in June. Our hypothesis was that corn yield in the roll-killed, June-planted vetch treatment with post-plant cultivation would be equivalent to, or better than, yield in a typical organic corn production system for our area (including mechanical incorporation of the vetch cover crop, a May planting date, and rotary hoe plus sweep cultivation for weed control). We also hypothesized that yield loss to weeds in the roll-killed, late-planted treatment would be lower than that in the tillage-based treatments.

MATERIALS AND METHODS

Site Description

Experiments were conducted at a field site on the North Farm of the USDA-ARS Beltsville Agricultural Research Center, Beltsville, MD (39°02′05″ N, 76°54′28″ W). This 9-ha field has been farmed using organic farming practices since 2000 and has been certified by the Maryland Department of Agriculture according to the USDA National Organic Program requirements since 2003. The field was divided into six approximately 1.5-ha areas that were rotated among alfalfa, small grain, and row crops, similar to rotations on well-managed organic grain or dairy farms in this region. The three corn experiments described in this article were conducted in 2008, 2009, and 2010 in successive 1.5-ha rotational areas within this larger certified organic field. The rotation for the 2 yr preceding each corn experiment consisted of alfalfa (*Medicago sativa* L.), wheat, and fall establishment of the hairy vetch cover crop. The soil was a Codorus–Hatboro silt loam (fine-loamy, mixed, active, mesic, Fluvaquentic Dystrudepts and Endoaquepts; 0–3% slope).

In early September preceding the three experimental years, potassium sulfate was applied at an average rate of 47 kg K ha^{-1}, fields were disked and packed, and hairy vetch seed was drilled at 34 kg ha^{-1}. The hairy vetch used in these experiments was a selection of the cultivar ‘AU Early Cover’ (Mosjidis et al., 1995) that had been locally grown in southeastern Pennsylvania for 11 seasons (S. Groff, Cedar Meadow Farm, Holtwood, PA). The following spring, experimental treatments were imposed on the vetch cover crop.

Treatments and Experimental Design

The experiment was arranged in a split-plot design with three splits. The whole plot was vetch termination method, the first split was vetch termination/corn planting date, the second split was presence or absence of post-plant cultivation, and the third split was presence or absence of weeds. The experimental unit was 3.0 m (four corn rows) wide by 7.6 m long. Treatments were arranged in a randomized complete block design with four replications.

Hairy vetch was terminated by either (i) disking twice to shallowly (10 cm) incorporate vetch or (ii) rolling with a commercially built roller-crimper (I and J Manufacturing, Gap, PA) to leave vetch on the soil surface. Termination was performed at three stages of vetch development: (i) late vegetative, (ii) 75% flowering, or (iii) early pod in the disk-killed treatment (Table 1). Because the roller-crimper does not effectively kill hairy vetch in the vegetative stage (Hoffman et al., 1993; Mischler et al., 2010), the roll-killed treatment was only applied at the 75% flowering and early pod stages.

Corn planting was scheduled for 7 d after hairy vetch termination; however, rainfall followed by wet soil conditions delayed this operation by 3 to 17 d in several instances (Table 1). In the disk-kill treatment, plots were disked two more times to thoroughly incorporate the remaining vetch residue, cultipacked, and planted. In the roll-killed treatment, a second rolling operation was performed by the roller-crimper

Table 1. Dates of hairy vetch termination, corn planting, and corn physiological maturity (grain black layer formation), along with hairy vetch dry matter (DM) biomass and N content at termination, water available for corn growth, and radiation available for corn growth at each date in each year. Standard errors are presented in parentheses.

Year	Hairy vetch termination date†	Hairy vetch biomass	Hairy vetch N content	Corn planting date	Corn black layer date	Water available to corn‡	Radiation available to corn§
		kg DM ha^{-1}	kg ha^{-1}			mm	kW m^{-2}
2008	2 May	4930 (270)	183 (09)	26 May	15 Sept.	419	24.5
	30 May	7110 (240)	272 (13)	9 June	24 Sept.	365	22.3
	13 June	6630 (190)	223 (10)	20 June	16 Oct.	378	23.0
2009	28 Apr.	4030 (020)	178 (06)	14 May	3 Sept.	582	22.0
	3 June	4610 (190)	159 (09)	16 June	19 Oct.	472	22.4
	16 June	3330 (280)	85 (07)	30 June	16 Nov.	535	21.5
2010	30 Apr.	4390 (220)	165 (03)	7 May	26 Aug.	515	23.0
	14 May	5120 (270)	152 (17)	21 May	14 Sept.	502	25.2
	1 June	5760 (230)	135 (12)	8 June	6 Oct.	582	24.6

† Hairy vetch termination dates were targeted to coincide with late vegetative, 75% flowering, and early pod developmental stages.

‡ Sum of soil water to 30 cm at the time of planting plus rainfall and irrigation from corn planting to black layer.

§ Sum of radiation received from corn emergence to black layer.

mounted on the front of the tractor while planting was performed by a planter pulled behind the tractor. Corn (Blue River 49M37, 105-d relative maturity, certified organic seed) was planted 4 cm deep on 76-cm rows at 80,300 seeds ha^{-1} with a no-tillage planter equipped with a straight coulter, but without row cleaners to minimize disruption of the vetch residue. Each termination method by planting date plot area was split into (i) a 4-row (3.0 m wide) plot that received post-plant cultivation or (ii) an adjacent 4-row plot that was not cultivated. For the disk-killed treatments, post-plant cultivation involved rotary hoeing twice at approximately 1 and 2 wk after planting and two between-row sweep cultivations at approximately 4 and 5 wk after planting. For the roll-killed treatments, post-plant cultivation involved two between-row cultivations with a high-residue cultivator that minimally disrupted surface residue (Nord et al., 2011; Smith et al., 2011) at approximately 4 and 5 wk after planting. Plots received 51 mm of overhead irrigation in 2008 and 2009, and 102 mm in 2010.

Each cultivation plot was split into two 7.6-m long experimental units that were either (i) maintained weed-free by handweeding or (ii) left with the weed population remaining after treatment operations, designated hereafter as weedy plots. One exception in 2008: the post-plant cultivation treatment was split into both a weedy and weed-free treatment, but the uncultivated treatment had only a weedy treatment. The weedy plots were populated with the natural field weed flora in 2008, or were supplemented with weed seed in 2009 and 2010. Supplementation was made with a mixture of summer annual weeds typical of organic fields in this region consisting of equal numbers of common ragweed (*Ambrosia artemisiifolia* L.), giant foxtail (*Setaria faberi* Herrm.), and smooth pigweed (*Amaranthus hybridus* L.), each broadcast at 450 seeds m^{-2}. Seeds were spread evenly on the soil surface in late fall or early winter in weedy plots of the roll-kill treatment. In weedy plots of the disk-killed treatment, seeds were buried in nylon mesh bags during winter, exhumed the day of planting, dried with a hair dryer, and spread evenly over the plots to simulate seed that would naturally reside in the soil over winter and be brought to the surface by tillage at planting.

Measurements and Analyses

Above-ground hairy vetch biomass was collected from 1-m^2 quadrats adjacent to each block just before vetch termination, dried at 55°C for dry biomass determination, and ground for analysis of N content by combustion (Elementar Vario Max N/C Analyzer, Penn State University Agricultural Analytical Services Lab, University Park, PA). Aboveground weed biomass was collected from a 0.76 by 1.3 m (1-m^2) area between the middle two corn rows beginning 1.5 m from the end of each plot at corn silking. Corn population and grain yield were determined from 4.6 m in 2008, and 3.0 m in 2009 and 2010 of the middle two corn rows in each plot at physiological maturity (grain black layer). Corn ears were hand harvested, dried and shelled, and grain mass adjusted to 155 g kg^{-1} moisture content. Weather data were collected at a station located 0.26 km from the experimental fields.

Weed biomass, corn population, and grain yield were analyzed for each year separately by mixed model analysis of variance (PROC MIXED, SAS Version 9.1, SAS Institute, Cary, NC). Data from each year were analyzed separately because the three levels of planting date varied considerably from year to year (Table 1), rendering a uniform treatment coding for planting dates across years as unrepresentative of actual treatment levels. Corn population and grain yield were analyzed with hairy vetch termination method, corn planting date nested within termination method, post-plant cultivation, and weed level as fixed factors, and block and appropriate split-plot error terms as random factors. Corn planting date was nested within termination method because there were three planting dates within the disk-killed treatment, but only two levels within the roll-killed treatment. Because of the absence of a weed-free treatment in the post-plant cultivation treatment in 2008, this analysis could not test for interactions between cultivation and weeds in that year. The mixed model for analyzing weed biomass was similar to that used for corn population and yield except without the weed split, because these data were only collected from weedy subplots.

Weed control was computed as the percentage reduction in weed biomass in post-plant cultivated plots relative to the corresponding uncultivated treatment mean. Weed control was analyzed in response to termination method and planting date. Yield loss to weeds was computed as the percentage reduction in yield in weedy plots relative to the corresponding weed-free treatment mean. Yield loss was analyzed in response to termination method, planting date, and post-plant cultivation. Where fixed effects were significant, means were separated using the PDIFF option ($P < 0.05$) in the LSMEANS statement of PROC MIXED. Pearson correlations between corn grain yield, weed biomass, and corn population were determined within each year using PROC CORR of SAS. Multiple regression of corn grain yield as a function of weed biomass and corn population within each year was performed using PROC MIXED with block as a random variable.

RESULTS

Hairy vetch biomass increased each year between late April and early June and then declined thereafter (Table 1). Biomass and N content of vegetative hairy vetch at the first termination date in late April/early May was high, with more than 4000 kg dry matter (DM) ha^{-1} of biomass containing 165 to 183 kg N ha^{-1}. The relatively early hairy vetch planting dates for this location ranging from 4 to 7 September allowed for sufficient growing degree days to accumulate to achieve high levels of hairy vetch biomass by early May (Teasdale et al., 2004; Cook et al., 2010). Although hairy vetch biomass increased between vegetative and flowering stages, N content increased in only 1 of 3 yr. Hairy vetch N content declined 11 to 47% after full bloom, due to senescence of leaves and declining N concentration in vetch tissue. Although hairy vetch N content at the early pod stage was lower than at earlier developmental stages, a substantial portion of the lost vetch N presumably was still available for subsequent crop use in the form of decomposing or recently decomposed residue.

Weed Control

There were significant ($P < 0.05$) effects involving vetch termination method, planting date, and cultivation on weed biomass in each year (Table 2), so the termination method × planting date × cultivation interaction is shown in Table 3. Supplementing the weed seedbank of weedy plots in 2009 and 2010 led to higher overall weed biomass compared with

Table 2. Probability values for fixed effects from the analysis of variance of weed biomass, weed control, corn population, corn grain yield, and yield loss to weeds in response to hairy vetch termination method (T), planting date (D), presence or absence of post-plant cultivation (C), and presence or absence of weeds (W).

Year	Fixed effect	Weed biomass	Weed control	Corn population	Corn yield	Yield loss to weeds
		Probability > F				
2008	T	0.177	0.000**	0.000**	0.871	–
	D(T)	0.025*	0.792	0.010*	0.490	–
	C	0.001**	–	0.273	0.675	–
	T*C	0.014*	–	0.008**	0.237	–
	D*C(T)	0.108	–	0.004**	0.587	–
	W	–†	–	0.719	0.558	–
	T*W	–	–	0.552	0.670	–
	D*W(T)	–	–	0.290	0.792	–
2009	T	0.006**	0.052	0.216	0.536	0.238
	D(T)	0.002**	0.089	0.234	0.055	0.016*
	C	0.000**	–	0.029*	0.000**	0.000**
	T*C	0.812	–	0.832	0.248	0.518
	D*C(T)	0.633	–	0.063	0.902	0.250
	W	–	–	0.012*	0.000**	–
	T*W	–	–	0.030*	0.064	–
	D*W(T)	–	–	0.020*	0.001**	–
	C*W	–	–	0.003**	0.000**	–
	T*C*W	–	–	0.290	0.949	–
	D*C*W(T)	–	–	0.088	0.448	–
2010	T	0.000**	0.318	0.084	0.023*	0.103
	D(T)	0.000**	0.306	0.029*	0.013*	0.029*
	C	0.000**	–	0.907	0.019*	0.001**
	T*C	0.045*	–	0.987	0.743	0.051
	D*C(T)	0.045*	–	0.406	0.861	0.567
	W	–	–	0.007**	0.000**	–
	T*W	–	–	0.124	0.032*	–
	D*W(T)	–	–	0.995	0.037*	–
	C*W	–	–	0.073	0.007**	–
	T*C*W	–	–	0.387	0.215	–
	D*C*W(T)	–	–	0.790	0.842	–

* Significant at $P < 0.05$.

** Significant at $P < 0.01$.

† The dash indicates fixed effects that were not included in the model.

Table 3. Weed dry matter (DM) biomass and weed control at corn silking in weedy plots with or without post-plant cultivation. Weed seedbanks consisted of natural populations in 2008, and supplemented populations in 2009 and 2010.

Year	Hairy vetch management	Corn planting date	Weed biomass		Weed control†
			Minus cultivation	Plus cultivation	
			—— kg DM ha^{-1} ——		%
2008	Disk	26 May	1580 a‡	160 b	90 a
		9 June	570 b	20 b	96 a
		20 June	950 b	60 b	94 a
	Roll	9 June	1080 ab	610 ab	43 b
		20 June	1040 ab	790 a	23 b
2009	Disk	14 May	4040 c	1230 b	70 a
		16 June	5800 bc	1530 b	74 a
		30 June	4050 c	870 b	79 a
	Roll	16 June	6170 b	2190 b	64 a
		30 June	8430 a	5170 a	39 b
2010	Disk	7 May	6050 a	2400 a	60 a
		21 May	6840 a	2910 a	58 a
		8 June	3960 b	1790 ab	55 a
	Roll	21 May	3930 b	880 b	78 a
		8 June	1490 c	630 b	58 a

† Weed control was computed as the percentage reduction in weed biomass in cultivated plots relative to the corresponding uncultivated treatment mean.

‡ Values followed by the same letter within columns and years are not significantly different ($P < 0.05$).

unsupplemented weedy plots in 2008. Mean weed biomass in uncultivated plots was 5700 and 4450 kg DM ha^{-1} in 2009 and 2010, respectively, compared with 1040 kg ha^{-1} in 2008. The supplemented species, giant foxtail and smooth pigweed, dominated the weed community in 2009 and 2010, whereas natural populations in 2008 were composed of several annual species including carpetweed (*Mollugo verticillata* L.), tumble pigweed (*Amaranthus albus* L.), large crabgrass [*Digitaria sanguinalis* (L.) Scop.], goosegrass [*Eleusine indica* (L.) Gaertn.], and foxtail (*Setaria*) species.

When hairy vetch was terminated by disking and received no post-plant cultivation, weed biomass was lower when corn was planted in June than May in 2 of 3 yr (Table 3). This finding confirms previous research that shows reduced weed biomass by delaying corn planting date (Williams, 2006). Planting date did not result in any difference in weed biomass when disk-killed hairy vetch received post-plant cultivation (Table 3). Mean weed control in disk-kill treatments ranged from 58% in 2010 when weed pressure was high to 93% in 2008 when weed pressure was low.

When hairy vetch was terminated by roller-crimper and received no post-plant cultivation, weed biomass was most variable at the latest planting date, having the highest weed biomass in 2009, but lowest in 2010 (Table 3). Hairy vetch biomass at the late planting date in 2009 was 42 to 50% lower than that obtained in the other 2 yr (Table 1). This low level of residue and the very late planting date at the end of June in 2009 resulted in weed emergence before corn was planted, thus giving weeds a competitive advantage. Within the post-plant cultivated treatments, the late planted roll-killed treatment also was highly variable across years, exhibiting the highest weed biomass and the lowest weed control in 2 of 3 yr (Table 3).

Corn Population and Yield

There was a significant ($P < 0.05$) hairy vetch termination method × planting date × cultivation interaction for corn population in 2008 (Table 2). In this year, roll-killed hairy vetch reduced corn population compared with most disk-tilled treatments. Inspection of plants revealed damage by southern corn rootworm (*Diabrotica undecimpunctata howardi* Barber, D. Weber, USDA-ARS, Beltsville, MD, personal communication). In 2009, there was a significant hairy vetch termination method × planting date × weed interaction and a cultivation × weed interaction for corn population (Table 2), that were driven primarily by the low corn population in the weedy late-planted roll-killed treatment relative to all other treatments (Table 4). This was probably the result of the excessively high and competitive weed biomass in this treatment in that year (Table 3). In 2010, the only significant treatment effects on corn population included a 4% reduction in weedy vs. weed-free treatments (71,500 vs. 74,600 plants ha^{-1}) and a 7% reduction in the disk-killed/second planting date treatment vs. all other kill-date treatments (68,900 vs. 74,200 plants ha^{-1}).

In 2008, there were no significant ($P < 0.05$) corn grain yield differences among treatments (Table 2). The overall mean yield was 8.01 Mg ha^{-1} (standard deviation = 1.65). Despite the substantial corn population reductions sustained in 2008, corn was able to compensate, resulting in equivalent yields across all treatments.

In 2009 and 2010, there was a significant hairy vetch termination method × planting date × weed interaction for corn grain yield (Table 2). There were few significant differences among vetch termination method/planting date treatments in the absence of weeds (Table 5), demonstrating the high yield potential for all treatments in the absence of weed competition (weed-free yields averaged 11.69 and 9.89 Mg ha^{-1} in 2009 and 2010, respectively). The highest yields in the presence of weeds occurred at the last planting date, specifically in the disk-killed treatment in 2009 and the roll-killed treatment in 2010 (Table 5). The roll-killed/late-planted treatment in the presence of weeds had the most variable yields, having the lowest yield in 2009 and the highest yield in 2010. Substantial yield losses from weeds were sustained by all hairy vetch management and planting date treatments in the presence of high weed pressure in 2009 and 2010.

Table 4. Corn population for the hairy vetch management by corn planting date by post-plant cultivation interaction in 2008 and for the vetch management by planting date by weed interaction in 2009.

Hairy vetch management	Corn planting date	Corn population			
		2008		2009	
		Minus cultivation	Plus cultivation	Weed-free	Weedy
		—— plants ha^{-1} ——			
Disk	May	73,600 a†	71,000 a	78,300 a	77,800 a
	mid-June	65,700 a	66,400 ab	69,400 a	72,100 a
	late June	68,500 a	47,000 c	75,100 a	70,200 a
Roll	mid-June	47,000 b	44,500 c	72,900 a	72,400 a
	late June	47,400 b	58,100 b	77,000 a	59,700 b

† Values followed by the same letter within columns are not significantly different ($P < 0.05$).

Table 5. Corn grain yield and yield loss to weeds for the hairy vetch management by corn planting date by weed interaction in 2009 and 2010, averaged over post-plant cultivation treatments.

Year	Hairy vetch management	Corn planting date	Corn yield		Yield loss to weeds†
			Weed-free	Weedy	
			Mg ha^{-1}		%
2009	Disk	14 May	11.86 a‡	6.10 bc	49.9 ab
		16 June	11.17 a	6.03 bc	47.7 ab
		30 June	11.55 a	9.05 a	21.6 c
	Roll	16 June	11.68 a	7.77 ab	33.7 bc
		30 June	12.02 a	4.05 c	65.0 a
2010	Disk	7 May	10.19 ab	5.12 b	49.4 ab
		21 May	9.32 ab	3.00 c	67.3 a
		8 June	8.22 b	4.78 bc	37.7 bc
	Roll	21 May	10.19 ab	5.71 b	44.1 ab
		8 June	10.89 a	9.25 a	15.8 c

† Yield loss to weeds was computed as the percentage reduction in yield in weedy plots relative to the corresponding weed-free treatment mean.

‡ Values followed by the same letter within columns and years are not significantly different ($P < 0.05$).

Table 6. Corn grain yield and yield loss to weeds for the post-plant cultivation by weed interaction in 2009 and 2010, averaged over hairy vetch management/planting date treatments.

Year	Cultivation	Corn yield		Yield loss to weeds†
		Weed-free	Weedy	
		Mg ha^{-1}		
2009	plus	11.68 a‡	9.24 b	21.2 b
	minus	11.70 a	3.72 c	67.9 a
2010	plus	9.87 a	7.06 b	28.2 b
	minus	9.90 a	4.72 c	53.3 a

† Yield loss to weeds was computed as the percentage reduction in yield in weedy plots relative to the corresponding weed-free treatment mean.

‡ Values followed by the same letter within years are not significantly different ($P < 0.05$).

In 2009 and 2010, there was a significant cultivation × weed interaction for corn yield, but no significant interactions between cultivation and either termination method or planting date (Table 2). Post-plant cultivation had no influence on yield in the absence of weeds, but cultivation improved yield in the presence of weeds in these 2 yr with high weed pressure (Table 6). Although cultivation reduced corn yield loss substantially, it did not eliminate yield loss. Yield reductions of 21 to 28% were still sustained with cultivation. This level of corn yield reduction to weeds is comparable to that observed in long-term organic systems (Cavigelli et al., 2008).

Correlation and regression analysis confirmed that weed biomass had no significant effect on corn yield in 2008 when weed population was low, but had a substantial impact in 2009 and 2010 when weed populations were supplemented (Table 7). In 2009 and 2010, weeds reduced corn grain yield at a rate of approximately 1 kg of grain for every 1 kg of weed biomass. Corn population was not correlated to corn yield in 2008 (Table 7); however, corn population was positively correlated to corn yield in 2009 and 2010. When both corn population and weed biomass were evaluated in a multiple regression analysis, population was still significantly related to yield in 2009, suggesting that population had an independent effect on crop yield, probably driven by the association of low yield and

Table 7. Pearson correlation coefficients between corn grain yield and weed biomass or corn population and multiple regression coefficients for corn yield as a linear function of weed biomass and corn population.

Year	Correlation coefficients: Weed biomass	Correlation coefficients: Corn population	Multiple regression coefficients: Weed biomass	Multiple regression coefficients: Corn population
			kg kg^{-1}	kg plant^{-1}
2008	−0.184ns†	0.150ns	−0.51ns	0.021ns
2009	−0.839***	0.596***	−1.01***	0.098***
2010	−0.803***	0.368**	−1.12***	0.041ns

** Significant at $P < 0.01$.

*** Significant at $P < 0.001$.

† Not significant at $P = 0.05$ (ns).

low population in the roll-kill/late planted treatment in that year. When population was combined with weed biomass in a multiple regression analysis of 2010 data, population was no longer significantly related to yield, suggesting that population did not independently affect crop yield in that year.

DISCUSSION

Impact of Planting Date and Tillage on Corn Yield

Our hypothesis that corn grain yield in the roll-killed, June-planted treatment with post-plant cultivation would be equivalent to, or better than, yield in a typical tillage-based organic corn production system was confirmed, as long as planting was not delayed until late June. There were no yield differences between roll-killed and disk-killed treatments in 2008. There were no yield differences in 2009 between the roll-killed treatment with a 16 June corn planting date and any disk-killed treatment under either weedy or weed-free conditions (Table 5). Corn yield in 2010 in the 8 June roll-killed, planting date treatment was similar to the best disk-killed treatments under weed-free conditions and exceeded all disk-killed treatments under weedy conditions. Only when planting was delayed until 30 June in 2009 was corn yield lower in the roll-killed than in the disk-killed treatment under weedy conditions, primarily because of partial senescence of vetch coupled with early weed emergence in this roll-killed treatment. This late planting date would be undesirable, regardless, because it would delay corn harvest and subsequent fall cover crop establishment. Cereal cover crops are commonly deployed after corn in the mid-Atlantic region to scavenge N and reduce erosion (Shipley et al., 1992; Brandi-Dohrn et al., 1997). These ecosystem services that are critical to organic and conventional farming operations in this region would be significantly reduced or eliminated with delay in fall establishment.

Planting date had little influence on corn yield in these experiments. Although it was anticipated that planting date could influence corn yield by impacting soil moisture, solar radiation, soil fertility, and weed abundance, planting date had little impact on these parameters other than weed abundance. Weather data showed that planting dates had little influence on the availability of moisture and radiation to corn (Table 1). Even when corn was planted mid to late June, there was a sufficiently long growing season at this mid-Atlantic location for corn to reach physiological maturity and receive similar radiation as earlier planted corn. Hairy vetch had already reached more than 4000 kg ha^{-1} of biomass containing 165 to 183 kg N ha^{-1} by the first termination date in late April/early May, and in 2 of 3 yr peak N content was achieved at the first termination date (Table 1). In addition, these fields had been conditioned with several years of alfalfa during the transition period to organic certification, so N fertility levels were relatively high. Corn earleaf N concentration averaged 3.41, 3.02, and 3.11% in weed-free treatments in 2008, 2009, and 2010, respectively, testifying to the N sufficiency in these fields (Mills and Jones, 1996). Delayed hairy vetch termination dates did reduce weed biomass in 2 of 3 yr within the disk-kill treatment when no cultivation was employed (Table 3). However, post-plant cultivation essentially erased this difference; there were few effects of vetch termination date on weed biomass following cultivation, and there were few termination date effects on weed control efficacy by cultivation. Thus, given the similarity in weed biomass after cultivation, fertility, moisture, and radiation across planting dates, it is not surprising that delayed hairy vetch termination/corn planting dates had little impact on corn yield. Other research in Pennsylvania has shown that delayed hairy vetch termination dates also had no consistent effect on corn yield (Cook et al., 2010; Mischler et al., 2010).

Impact of Planting Date and Tillage on Weed–Crop Competition

Our hypothesis that corn yield loss to weeds would be lower in the roll-killed, late-planted system than in the disk-killed treatments was partially supported. The 16% loss sustained in the roll-killed/late planted treatment in 2010 was the lowest loss observed among kill-date treatments, and the yield in weedy plots in this treatment was the highest among all other weedy treatments (Table 5). However, besides this treatment, there was substantial yield loss to weeds by the other roll-killed treatments in 2009 and 2010. Ideally, roll-killed hairy vetch will leave a dense layer of residue on the soil surface that can suppress weed emergence if mulch levels are sufficiently high. However, an estimated 7000 kg DM ha^{-1} of hairy vetch residue is required to reduce redroot pigweed emergence by 80% (Teasdale and Mohler, 2000). This level of hairy vetch biomass was only achieved in 1 yr in this experiment and is rarely achieved, even with optimum planting dates (Teasdale et al., 2004). Smith et al. (2011) found that roll-killed rye residue levels exceeding 8000 kg DM ha^{-1} were needed to consistently suppress weeds in soybean production. Considering these high residue biomass levels that are required to suppress weeds, hairy vetch will likely need to be mixed with rye to achieve sufficient residue levels to consistently eliminate weed interference in corn production. Future research on small grain/hairy vetch mixtures should identify proportions that optimize biomass while maintaining sufficient available N for corn production.

Although high surface mulch residue levels are required for weed suppression, they can also interfere with planting operations and reduce crop stand. The highest degree of corn stand reduction in these experiments occurred in roll-killed treatments in the year with the highest hairy vetch biomass (6630–7110 kg DM ha^{-1} at the second and third termination dates in 2008). Most researchers that have worked with roller-crimper systems report reduced crop stand, delayed crop development, and/or increased crop lodging (Davis, 2010; Mischler et al., 2010; Smith et al., 2011; Vaisman et al., 2011). It will be challenging to balance the need for sufficiently thick residue levels to suppress weeds against the potential detrimental mulching effects on crops caused by inadequate seed placement, cool soils in northern climates, seedling etiolation leading to weakening of crop support tissue, and harboring seedling-destructive insect populations. Systems that could open strips in the cover crop residue within row during planting and crop establishment, but then move residue back into the row area to control weeds during cultivation may be a feasible approach to alleviate this dilemma.

Weed control in the roll-killed organic systems will, in most cases, require supplemental post-plant cultivation with a high residue cultivator, given the inconsistency of cover crop residue for providing full-season weed suppression (Drinkwater et al., 2000). The efficacy of high residue cultivation in the roll-killed treatment in our experiments was poorer and less consistent than that in the disk-killed treatment (averaged across all years, weed control was 51% vs. 75% with a standard deviation of 32 vs. 19 in the roll-killed vs. disk-killed treatments, respectively). This result confirms earlier research that demonstrated reduced efficacy of cultivation in mowed or chopped hairy vetch residue than in clean-tilled soil (Teasdale and Rosecrance, 2003). The net combination of incomplete weed suppression by hairy vetch mulch plus relatively low-efficacy cultivation in the roll-killed system resulted in weed control that was not an improvement over that obtained in the disk-tilled treatments. Overall yield losses across all vetch management/planting date treatments that ranged from 21 to 28% in post-plant cultivated treatments (Table 6) were only observed in the years when the natural weed seedbank was supplemented, which points to weed seedbank size as an important factor impacting corn yield loss to weeds. In 2008, when seedbank size was relatively low, there were no significant effects of weeds on corn yield. Thus, given the inability of post-plant cultivation to completely rescue corn production from high weed populations, maintaining a low weed seedbank should be a priority for the success of organic roll-killed grain production systems.

In summary, development of reliable weed control systems for roller-crimper based organic production systems will require high cover crop biomass, improved efficiency of high residue cultivators, and crop rotational strategies that maintain a low weed seedbank. In addition, to ensure adequate crop population and growth, improved equipment for planting through thick cover crop residue and strategies for managing residue to alleviate adverse corn seedling effects will be required. Roller-crimper technology will be most effective at providing organic growers with the benefits of conservation tillage if used intermittently within a broader rotation of crops and tillage where weeds, pests, and fertility can be adequately managed.

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