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Hairy Vetch Management for No-Till Organic Corn Production

Ruth Mischler, Sjoerd W. Duiker,* William S. Curran, and David Wilson

ABSTRACT

Rolling-crimping to control hairy vetch (*Vicia villosa* Roth) may make organic no-till corn (*Zea mays* L.) possible. This study investigated how rolling-crimping date and growth stage of the cover crop affected hairy vetch control and if a rolled-crimped hairy vetch cover crop could supply weed control for no-till corn. Hairy vetch was planted in late August and was rolled and crimped and planted to corn at four dates ("planting dates") between late May and late June at three Pennsylvania locations. Hairy vetch biomass, measured at each planting date, varied from 2000 to 8000 kg ha^{-1}. Hairy vetch control with the roller-crimper varied through the flowering stage and was consistent after early pod set. The hairy vetch cover crop reduced weed density by at least 50%, with annual weeds being affected more than perennials. Total weed biomass was reduced 31, 93, and 94% in different site-years compared with no-cover plots. As corn planting dates were delayed, greater amounts of vetch mulch and lower weed density helped reduce weed biomass. Corn yields in the organic no-till system with a hairy vetch cover crop ranged from 1.1 Mg ha^{-1} to 9.6 Mg ha^{-1}. Low yields were attributed to incomplete control of hairy vetch, weed competition, reduced corn plant populations, increased insect pests, and possibly inadequate N supply. This study shows that it is possible to kill hairy vetch with a roller-crimper and provide weed control for organic corn, resulting in reasonable corn yields, but that production risk increases.

Organic food sales in the United States have more than quintupled since the late 1990s from $3.6 billion in 1997 to $21.1 billion in 2008, and now account for 3% of U.S. food sales (Greene et al., 2009). Organic food is sold with the premise that it is more sustainably produced. However, annual crop production in organic systems relies heavily on tillage for seedbed preparation and weed control. Intensive tillage is labor and energy intensive; exposes the soil to erosion and water use inefficiencies due to increased runoff and evaporation; and reduces physical, chemical, and biological soil quality (Pimentel et al., 1995; Wang et al., 2002). No-tillage crop production addresses these concerns (Hartwig and Ammon, 2002; Uri, 2000). No-till was used on 25.3 million ha in the United States in 2004, an increase of 5.5% nationwide from 2000 (Conservation Technology Information Center, 2004). However, no-till as currently practiced relies heavily on herbicides for weed control, an unaccepted practice in organic production. Recent efforts are exploring opportunities to enable no-till without herbicides by using cover crops to help control weeds (Teasdale et al., 2007; Yenish et al., 1996).

Living cover crops suppress weeds through competition for light, moisture, and nutrients. Dead cover crops can suppress weeds if the mulch is left on the soil surface. Rolling-crimping with a hollow drum with blunt blades is an emerging method to kill cover crops without herbicides while leaving the dead mulch at the surface, making organic no-till crop production possible. This method crushes the vascular tissue of cover crops without completely cutting the stems. If done at a certain growth stage, the cover crops will die after this operation, while the residue is placed flat on the soil surface. For example, cereal rye (*Secale cereale* L.) was killed successfully by rolling-crimping once it reached anthesis (Ashford and Reeves, 2003; Mirsky, 2008). Hairy vetch was successfully killed by rolling-crimping at late bloom, but not at early bud or mid bloom (Hoffman et al., 1993). In another study, however, rolling-crimping hairy vetch in the vegetative stage provided at least 80% kill with complete kill at 20% bloom in a Mississippi study (Creamer and Dabney, 2002). Hairy vetch is a winter-hardy, leguminous cover crop suited for the northeastern region of the United States that provides weed control and moisture conservation, and can supply most N needs of the following corn (Brandsaeter and Netland, 1999; Clark et al., 1995; Ebelhar et al., 1984; Ruffo and Bollero, 2003; Teasdale et al., 2004). Hairy vetch produced more dry matter with a higher N concentration than big flower vetch (*Vicia grandiflora* W. Koch var. 'Kitailbeliana') or crimson clover (*Trifolium incarnatum* L.) (Ebelhar et al., 1984; Hargrove, 1986; Holderbaum et al., 1990). Teasdale et al. (2003) showed that hairy vetch reduced grass emergence by 50 to 90%, while other work showed that hairy vetch adequately suppressed summer annual weeds and yellow nut sedge (*Cyperus esculentus* L.) (Reddy and Koger, 2003). In contrast, another study showed no difference in weed biomass between a hairy vetch cover crop and no cover crop (Yenish et al., 1996). In fact, the hairy vetch cover crop reduced corn yield in this study because it was not completely controlled and competed with the crop. Other research suggests that twice as much hairy vetch residue as is typically produced would be required to satisfactorily reduce emergence of a variety of weed seedlings (Mohler and Teasdale, 1993).

Dep. of Crop and Soil Sci., The Pennsylvania State Univ., 116 ASI Bldg., University Park, PA 16802-3504. Received 6 May 2009. *Corresponding author (sduiker@psu.edu).

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Abbreviations: WAP, weeks after planting

The referenced studies suggest that successful mechanical control of hairy vetch is linked to its phenology, while weed suppression by the cover crop will be impacted by both the quantity and quality of the surface mulch. To further our knowledge of hairy vetch management for no-till organic corn production, this trial was designed to determine (i) at what life-stage hairy vetch can be killed by a roller-crimper, (ii) how timing of hairy vetch rolling-crimping influences weed suppression, and (iii) the effect of hairy vetch and its kill date (and associated with that, corn planting date) on corn grain yield.

MATERIALS AND METHODS

Field Management

A field trial was established in 2006 at "Rodale" (The Rodale Institute research farm, Kutztown, PA, 40°33′ N, 75°43′ W) and at "Rock Springs" (Penn State University Russell E. Larson Agricultural Research Center, Centre County, PA, 40°44′ N, 77°57′ W). A third location added to these two in 2007 was "Landisville" (the Penn State University Southeastern Research and Education Center, Landisville, Lancaster County, PA, 40°05′ N, 76°24′ W). The inclusion of these sites allowed us to study the potential of this management system under a range of climatic conditions ranging from relatively mild winters (Landisville) to colder winter temperatures at Rock Springs, whereas Rodale was intermediate. Overwinter survival of hairy vetch may be poorer and phenological development in the spring may be slower in colder winter conditions. At Rock Springs and Landisville, the experimental design was a modified split plot with corn planting date as the main plot, cover crop vs. no cover crop as a subplot, and herbicide vs. no herbicide as a sub-subplot treatment. Throughout this manuscript, "planting date" refers to corn planting date, which was the same day as hairy vetch rolling-crimping date. At Rodale the study was managed using certified organic practices and only corn planting date was examined in a randomized complete block design in which all plots were planted to hairy vetch in the fall. The soil type at Rodale was a Berks-Weikert silt loam, (well-drained, loamy-skeletal, active, mesic Typic Dystrudept), while it was a Hagerstown silt loam (well-drained, fine, mixed, semiactive, mesic Typic Hapludalf) at the other two locations. At Rodale, hairy vetch was drilled into tilled soil in late August of 2006 and 2007 at 20.8 kg ha^{-1} with 54 kg ha^{-1} oat (*Avena sativa* L.) as a nurse crop. At Rock Springs and Landisville, hairy vetch was no-till seeded into small grain stubble across the entire study area in late August or early September at 22.5 kg ha^{-1} with 54 kg ha^{-1} oat as nurse crop. To establish no-cover crop plots, 0.56 kg ha^{-1} 2,4-D low volatile ester ((2,4-dichlorophenoxy)acetic acid) was applied after hairy vetch emergence in mid to late November in these plots at Rock Springs and Landisville to control the cover crop. At Rodale the hairy vetch seed used in 2006 was produced in Nebraska (variety not stated), while in 2007, the seed was of the variety 'Auburn Early Cover' (Teasdale et al., 2004). At the other two locations only 'Auburn Early Cover' was used. The 'Auburn Early Cover' seed had been reproduced for many years by a Pennsylvania farmer, which probably caused a gradual adaptation of the vetch to Pennsylvania conditions.

The hairy vetch cover crop was rolled and crimped at four different dates (Table 1) with a roller-crimper in late spring and early summer of 2007 and 2008. The roller-crimper used in this study (I & J Manufacturing, Gap, PA) was 3.04 m wide and similar in design to the roller tested by Kornecki et al. (2006). The roller-crimper was constructed using a 41 cm diameter steel cylinder with blunt metal blades welded to the outside in a chevron pattern (Ashford and Reeves, 2003). The roller-crimper was filled with water at each rolling-crimping and weighed about 900 kg. The implement was front-mounted to the tractor and driven at 7.2 km h^{-1}. At Rock Springs in 2008, a slightly heavier (1520 kg) roller-crimper of similar design was used (Mirsky, 2008). Since the roller-crimper was followed immediately by corn planting, the combination of roller-crimper and no-till corn planter on hairy vetch control was assessed. The depth gauge wheels on the corn planter provided additional control of the vetch by crushing it.

Immediately following rolling, a 95 d corn hybrid 'Blue River 40M21' was no-till planted in a 76 cm row spacing into the hairy vetch residue. At both Rock Springs and Rodale a Monosem vacuum planter (Monosem Inc., Edwards, KS) and at Landisville a White no-till planter (Landoll Corporation, Maryville, KS) was used. The corn seeding rate was 79,000 seeds ha^{-1} at Rock Springs and Landisville and 84,000 seeds ha^{-1} at The Rodale Institute. At Rock Springs and Landisville, the plots without hairy vetch received N fertilizer applied at 112 kg N ha^{-1} before corn planting. This intermediate rate of fertilizer (90 to 100 kg ha^{-1} N to a corn crop) was selected to approximate the N contribution expected from the hairy vetch cover crop (Ebelhar et al., 1984). No N was applied to corn grown in plots with a hairy vetch cover crop. At Rock Springs, tefluthrin (2,3,5,6-tetrafluoron 4-methylphenyl) methyl-(1α, 3 α)-(Z))-(±)-3-(2-chloro-3,3,3-trifluoro-1-propenyl)-trifluoro-1-propenyl)-2–2-dimethylcyclopropone carboxylate) was applied at 3.7 kg a.i. ha^{-1} with the seed to control soil insect pests. Cyfluthrin (0-[2–1,1-Dimethyl)-5-pyrimidinyl]-0-ethyl 0-(1-methylethyl) phoshorothioate or cyano(4-fluoro-3-phenoxyphenyl)-methyl 3-(2,2-dichloroethenyl0–2,2-dimethylcyclopropanecarboxylate) at 3.4 kg a.i. ha^{-1} was used at Landisville.

At Rock Springs and Landisville, weed-free sub-subplots with and without hairy vetch received a foliar plus residual herbicide application (2.26 kg a.i. ha^{-1} s-metolachlor (2-chloro-*N*-(2-ethyl-6-methylphenyl)-*N*-[(1*S*)-2-methoxy-1-methylethyl]acetamide), 0.84 kg a.i. ha^{-1} atrazine (2-cholor-4-ethylamine-6-isopropylamino-1,3,5-triazine), 0.23 kg a.i. ha^{-1} mesotrione (2-[4-(methylsulfonyl)-2-nitrobenzoyl]-1,3-cyclohexanedione), and 0.86 kg a.e. ha^{-1} glyphosate (*N*-(phosphonomethyl)glycine)) shortly after corn planting to provide complete hairy vetch and weed control. The other sub-subplot treatments did not receive any herbicide. The intent of the herbicide treatment was to provide complete control of both the hairy vetch and weeds to compare the effects of the rolled-crimped cover crop and weeds on corn yield. The size of the main plots at Rock Springs in 2007 was 12.2 by 24.3 m, whereas subplots were 3 by 12.2 m. Individual sub-subplot size that received herbicide was 3 by 7.6 m, but the weed-free sub-subplot was 3 by 4.6 m. In 2007, main plots at Landisville and Rock Springs were 12.2 by 30 m, subplots 3 by 15.2 m, and sub-subplots 3 by 7.6 m. At Rodale, plots were 7.6 by 15 m in both years.

Hairy Vetch Growth Stage

Hairy vetch growth stage development was determined immediately before rolling-crimping and planting by two methods: (i) visual assessment method based on 0 to 100% flowering where 0

= no flowers present and 100 = complete flowering on the entire stem length and (ii) count method, where ten stems per plot were removed and the number of nodes, buds, flowers (any purple color on the raceme) and pods were determined. Percent flowering was calculated by taking the ratio of flowers and pods to the total number of nodes. The visual assessment method tended to overestimate vetch flowering stage and did not capture pod formation (Table 1). The count method used in 2007 more accurately captured flower stage but still did not capture pod set because it considered pods to be flowers. In addition, this method was cumbersome to use.

In 2008 the second method was therefore modified to include pod-set stages and to facilitate faster data collection. The first five nodes below the apical meristem were counted on two stems per plot. Nodes had to be at least 5 cm apart or the next sequential node was counted. Each node was recorded as a bud, flower, or pod to classify the growing stage as follows:

- Vegetative stage—all five nodes were buds
- 20% flowering—one node flowering out of five
- 40% flowering—two nodes flowering out of five
- 60% flowering—three nodes flowering out of five
- 80% flowering—four nodes flowering out of five
- 100% flowering—five nodes flowering out of five
- Early pod set—one or two nodes out of five contained pods with immature seeds (flattened and not hard)
- Mid pod set—three nodes out of five contained pods
- Late pod set—four or five nodes out of five contained pods and/or seeds were maturing in pods

Data Collection

Hairy vetch biomass was collected in two 0.5 m^2 quadrats per plot the same day the cover crop was rolled and crimped. Weeds were separated from the hairy vetch, and are not included in biomass measurements. However, few weeds were present at corn planting time. Samples were dried at 55°C for 72 h and weighed. Four weeks after planting (WAP), hairy vetch control in the entire plot was assessed visually for each plot on a 0 to 100% scale, where 0 = no control and 100 = complete control. The visual assessment was done by averaging across the entire plot area. In addition, to estimate regrowth after rolling, living hairy vetch was collected 4 WAP from two 0.5 m^2 quadrats in each cover crop plot that did not receive the herbicide treatment; these samples were dried and weighed. Some hairy vetch flowering and regrowth data were not collected at Rodale due to inclement

Table 1. Hairy vetch flowering percentage, biomass, percent control and regrowth at four corn planting dates† at three locations in Pennsylvania (2007–2008).‡

Corn planting	Date	Flowering: Visual method	Flowering: Count method§	Biomass	Control	Regrowth¶
		%	%	kg ha^{-1}	%	kg ha^{-1}
			Rock Springs 2007			
First	29 May	53	44	2903 b	69 c	2700 c
Second	2 June	70	61	3513 ab	82 b	1750 cb
Third	7 June	95	early pod	3969 ab	89 ab	1020 ab
Fourth	13 June	100	late pod	4459 a	100 a	0 a
			Rock Springs 2008			
First	30 May	0	10	1969 b	68 c	1990 b
Second	7 June	47	50	1991 b	87 b	850 a
Third	12 June	100	85	3290 a	99 a	0 a
Fourth	20 June	100	late pod	2990 a	99 a	0 a
			Landisville 2008			
First	29 May	41	45	2473 b	94 a	320 b
Second	6 June	66	58	2571 b	99 a	0 a
Third	12 June	100	early pod	3663 a	99 a	0 a
Fourth	18 June	100	mid pod	3973 a	99 a	0 a
			Rodale 2007			
First	30 May	55	58	6936 b	78 c	–
Second	7 June	65	62	7054 ab	89 b	–
Third	14 June	100	early pod	7376 ab	98 a	–
Fourth	21 June	100	late pod	7811 a	99 a	–
			Rodale 2008			
First	6 June	65	–	7808 a	93 b	–
Second	16 June	90	–	7956 a	99 a	–
Third	20 June	100	pods	7401 a	99 a	–
Fourth	25 June	100	pods	7798 a	99 a	–

† Corn planting was preceded by hairy vetch rolling-crimping operations on the same day.

‡ Numbers followed by the same letter within a column at a site-year combination are not significantly different (Tukey-Kramer mean separation at $P < 0.05$).

§ Counting method differed in 2007 and 2008 (see Materials and Methods).

¶ Some hairy vetch flowering and regrowth data were not collected at Rodale due to inclement weather and labor constraints.

weather and labor constraints. Corn stand was determined 4 WAP by counting the number of emerged plants in a center row of each plot for a 5.28 m length. Weed density was determined by counting all emerged weeds in three 0.5 m^2 quadrats per plot at 4, 8, and 12 WAP. Weed density was not measured at Rodale due to labor shortage. Weed biomass was harvested at all three locations 12 WAP from three 0.5 m^2 quadrats, dried at 55°C for 72 h and weighed. Weed species were grouped as annual broadleaves, annual grasses, and perennials.

Corn grain yield was harvested either mechanically (small plot combine) or by hand from the center two rows of each plot. In 2007, because of the smaller size of the weed-free sub-subplots at Rock Springs, grain yield was determined by hand-harvesting all four rows. All harvested corn was shelled using a small plot combine equipped with a scale and moisture recorder. All yields were standardized to 155 g kg^{-1} moisture.

Statistical Analysis

Effects of corn planting date (which was the same day as hairy vetch rolling-crimping), cover crop presence or absence and herbicide use or absence were tested as well as their interactions using PROC MIXED and Tukey-Kramer mean separations at a P value of 0.05 in SAS v. 9.1 (SAS Institute, 2008). Visual inspection of frequency distributions showed that normality assumptions were not being violated. A test for homogeneity of variance was performed using the residual error terms to determine if data could be pooled across locations and years. This analysis showed significant differences between locations at a P value of 0.0002 and between years at <0.0001, and therefore all data were analyzed separately for each location and year. Because weed density counts were performed in fixed subplots at 4, 8, and 12 WAP, typical of a repeated measures design, time was included in the model as a factor.

RESULTS

Hairy Vetch Development and Control

Hairy vetch was rolled and crimped based on growth stage at four dates at each location (Table 1). Roll-crimp dates varied from the end of May to the end of June to achieve desired growth stages. Percent flowering as determined by the visual method ranged from less than 50% at the earliest to 100% at the latest roll-crimp dates. Growth stage as measured using the count method ranged from 10% flowering to late pod stage. Hairy vetch biomass at the time of rolling-crimping ranged from approximately 2000 to 8000 kg ha^{-1} (Table 1). Biomass production varied depending on date and location. Hairy vetch biomass increased about 50 to 60% from the first to the last roll-crimp date at Rock Springs and Landisville. At the Rodale site, however, vetch aboveground biomass was approximately 7000 kg ha^{-1} or greater by the first roll-crimp date, with little additional growth after that. Hairy vetch control by rolling-crimping ranged from 68% to 100%. Regrowth was small if hairy vetch was rolled and crimped after pods were visible, but was considerable if rolled and crimped earlier in some cases. Hairy vetch rolled and crimped before pod set exhibited more regrowth in the moist summer of 2007 than in the dry summer of 2008.

Weed Control

A primary focus of this experiment was characterizing how timing of hairy vetch rolling-crimping suppressed summer annual weeds. The growing hairy vetch cover crop was extremely competitive and although weeds were not quantified before rolling-crimping, few or no weeds were observed before termination of the cover crop. Even in the no-cover treatments, few weeds were present before planting. The scarcity of winter or early-emerging spring annuals at Rock Springs and Landisville may have been due to the long-term corn–soybean–small grain rotations at the two research farms mixed with tillage reducing the opportunity for their success. In addition, the no-cover treatments received a 2,4-D application the previous fall to kill the emerged hairy vetch. This would have also removed susceptible winter annual weeds from those plots.

Weed density had to be analyzed separately for location and year. Since weed density data were not collected at Rodale they cannot be presented. We will focus on the effect of the hairy vetch and corn planting date on weed control, and only present the effect of herbicide on weed control for comparison purposes. Significance of main effects and interactions are presented in Table 2. At Rock Springs in 2007 the hairy vetch cover crop reduced average weed density approximately 67% in the plots planted at the first two planting dates, but not in those planted later (Table 3). Annual broadleaf weed density was reduced by the cover crop independent of planting date, but annual grass and perennial weed density was only reduced in plots planted to corn at the two earliest dates (Table 3). Weed density increased rapidly between 4 and 8 wk after planting in the plots planted at the two first planting dates without cover crop but not in those with a cover crop (Fig. 1). However, weed density did not increase in the

Table 2. Significance of effect of corn planting date†, cover crop presence or absence, herbicide application or absence, and sampling time, and their interactions on weed density, weed biomass, corn population, and corn yield at Rock Springs and Landisville, Pennsylvania, in 2007–2008.

	Rock Springs 2007				Rock Springs 2008				Landisville 2008			
	Weed density	Weed biomass	Corn population	Yield	Weed density	Weed biomass	Corn population	Yield	Weed density	Weed biomass	Corn population	Yield
Planting date	<0.0001	0.354	0.8985	0.3227	0.9552	0.2229	0.1255	<0.0001	0.0003	0.539	<0.0001	0.0009
Cover crop	<0.0001	0.0194	0.0685	0.2242	<0.0001	<0.0001	0.1252	0.005	<0.0001	<0.0001	0.168	0.0196
Herbicide application	na‡	na	na	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	0.0005
PD × CC	<0.0001	0.1911	0.9028	0.5044	0.851	0.2737	0.0083	0.2999	0.1104	0.3232	0.0176	0.0003
PD × HA	na	na	na	0.4543	0.7773	0.2229	0.1734	0.0004	0.0003	0.5391	<0.0001	0.0009
CC × HA	na	na	na	0.0465	<0.0001	<0.0001	0.0005	<0.0001	<0.0001	<0.0001	<0.0001	0.0014
PD × CC × HA	na	na	na	0.1799	0.5666	0.2737	0.0751	0.3619	0.1104	0.3232	0.3286	0.9038
Time	<0.0001	na	na	na	0.5099	na	na	na	0.3854	na	na	na

† Corn planting was preceded by hairy vetch rolling-crimping operations on the same day.

‡ na = not applicable; PD = planting date; CC = cover crop; HA = herbicide application; Time = 4, 8, and 12 wk after planting.

plots without cover crop planted to corn at the last two planting dates. At Rock Springs in 2008, average weed density was more than six times greater without cover crop than with cover crop in the absence of herbicide (Table 3). The cover crop provided a level of weed control that was similar to that of herbicides. The cover crop reduced the density of annual broadleaf and grass weeds, but not of perennial weeds. At Landisville in 2008, cover crop plots had half the weed density of no-cover plots in the absence of herbicide, independent of corn planting date. Broadleaf weed density was reduced by the cover crop, but not grass and perennial weed density. Additionally, weed density decreased as planting date was delayed, but this happened in both cover and no-cover plots. Annual broadleaf density was most affected by planting date.

Even though weed density was sometimes impacted by corn planting date, and thus hairy vetch rolling-crimping date, weed biomass was never impacted by it. There were also no interactions between planting date and cover crop, showing that although the cover crop accumulated more biomass, this did not improve the control of weeds as measured by weed biomass (Table 2). The hairy vetch cover crop (independent of when it was rolled and crimped) reduced weed biomass 31% compared with no cover at Rock Springs in 2007, and 93 and 94%, respectively at Rock Springs and Landisville in 2008 in the absence of herbicide (Table 4). The herbicide-treated plots provided complete weed control, providing a weed-free comparison. At Landisville and Rock Springs, the dominant annual broadleaf weeds included common ragweed (*Ambrosia artemisiifolia* L.), smooth and redroot pigweed (*Amaranthus* spp.), common lamb's-quarters

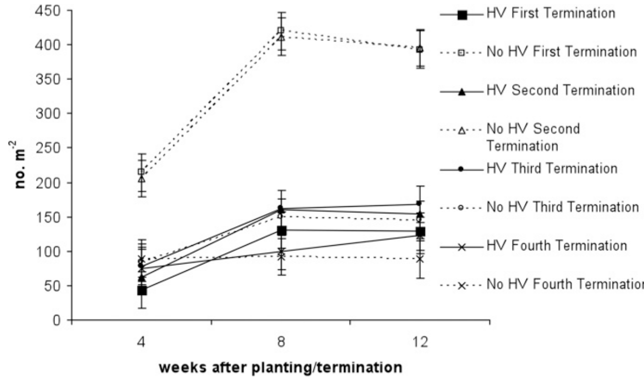

Fig. 1. Effect of corn planting–hairy vetch rolling-crimping date and hairy vetch cover crop on weed density at different times after planting (Rock Springs 2007). Error bars indicate standard error of the means.

Table 3. Effect of corn planting date†, cover crop, and herbicide application on weed density at Rock Springs (RS) and Landisville (LV), Pennsylvania, in 2007–2008, averaged across sampling time.‡

Location	Cover crop	Corn planting§	Herbicide¶	Broad leaves	Grasses	Perennials	Total
				no. m^{-2}			
RS 2007	Cover	1	–	12	25 a	54 a	96 a
		2	–	14	23 a	79 a	121 a
		3	–	13	19 a	96 ab	132 a
		4	–	13	24 a	62 a	99 a
		Mean		13 a	23	73	112
	No cover	1	–	10	95 ab	214 b	331 b
		2	–	29	174 b	119 ab	326 b
		3	–	21	40 a	58 a	122 a
		4	–	17	33 a	37 a	89 a
		Mean		19 b	86	107	217
RS 2008	Cover	–	No	7 a	8 a	6 b	21 a
		–	Yes	0 a	0 a	0 a	0 a
	No cover	–	No	55 b	68 b	10 b	134 b
		–	Yes	4 a	2 a	0 a	7 a
LV 2008	–	1	No	49 c	33	2 c	85 c
	–		Yes	0 a	0	0 a	0 a
	–	2	No	43 c	8	0 a	52 b
	–		Yes	0 a	0	0 a	0 a
	–	3	No	32 bc	4	1 b	36 b
	–		Yes	0 a	0	0 a	0 a
	–	4	No	27 b	14	3 c	47 b
	–		Yes	0 a	0	0 a	0 a
	Cover	–	No	20 b	14	2	36 b
		–	Yes	0 a	0	0	0 a
	No cover	–	No	57 c	16	1	74 c
		–	Yes	0 a	0	0	0 a
	–	–	No	38	15 b	2 b	55
			Yes	0	0 a	0 a	0

† Corn planting was preceded by hairy vetch rolling-crimping operations on the same day.

‡ Numbers in columns within a location-year combination followed by different letters were significantly different at $P < 0.05$ (Tukey-Kramer mean separation). If numbers are not followed by a letter, either the main effect or interaction were not significant.

§ Planting dates are listed in Table 1.

¶ 2.26 kg a.i. ha^{-1} s-metolachlor, 0.84 kg a.i. ha^{-1} atrazine, and 0.23 kg a.i. ha^{-1} mesotrione, and 0.86 kg a.e. ha^{-1} glyphosate.

Table 4. Average weed biomass in Rock Springs (RS) and Landisville (LV), Pennsylvania, in 2007–2008 as affected by hairy vetch cover crop and herbicide application.†

Cover Crop	Herbicide	RS 2007	RS 2008	LV 2008
		kg ha^{-1}		
Cover	No	905 a	520 a	460 a
	Yes	–	0 a	0 a
No cover	No	1320 b	7517 b	7641 b
	Yes	–	0 a	0 a

† Letters in columns indicate differences at P < 0.05 (Tukey-Kramer mean separation).

(*Chenopodium album* L.), velvetleaf (*Abutilon theophrasti* Medik.*),* Pennsylvania smartweed (*Polygonum pensylvanicum* L.), and more scattered populations of wild buckwheat (*Polygonum convolvulus* L.), yellow wood-sorrel (*Oxalis stricta* L.), hairy galinsoga (*Galinsoga ciliata* (Raf.) S. F. Blake), eastern black nightshade (*Solanum ptychanthum* Dunal), prostrate knotweed (*Polygonum aviculare* L.) and horseweed [*Conyza Canadensis* (L.) Cronquist]. The annual grasses giant and yellow foxtail (*Setaria* spp.) were common. Perennial weeds included yellow nut sedge (*Cyperus esculentus* L.), Canada thistle [*Cirsium arvense* (L.) Scop.], pokeweed (*Phytolacca Americana* L.), dandelion (*Taraxacum officinale* Weber in Wiggers), hemp dogbane (*Apocynum cannabinum* L.), oxeye daisy (*Chrysanthemum leucanthemum* L.), and plantain species (*Plantago* spp.).

At Rodale, the only variable was corn planting date, and no comparison between with and without cover are possible because all plots had a hairy vetch cover crop in the spring. In both years weed biomass differed between planting dates (Table 5). Weed biomass tended to be greatest in the plots planted earliest despite the fact that vetch biomass increased little between the first and last roll-crimp dates at Rodale. Observed species at Rodale included common ragweed, smooth and redroot pigweed, common lamb's-quarters, velvetleaf*,* Pennsylvania smartweed, curly dock (*Rumex crispus* L.), and giant foxtail (*Setaria faberi* R. A. W. Herrm.).

Corn Yield

Corn yields were affected by treatments in every site-year location (Tables 2, 5, and 6). Corn yields at Rock Springs in 2007 did not improve with a cover crop if no herbicide was used (Table 6). If herbicide was used, corn yields without cover crop were higher than those with cover crop on three planting dates, and were the same at one planting date. In 2008 the cover crop had a more favorable effect. Compared with no cover crop and no herbicide, the hairy vetch cover crop without herbicide use led to yield improvements of 6.0, 7.1, 7.4, and 4.7 Mg ha^{-1} at Rock Springs and 7.8, 6.0, 4.5, and 2.7 Mg ha^{-1} at Landisville, at the first, second, third and fourth corn planting dates, respectively. In fact, corn yields did not improve significantly due to the use of herbicide at Rock Springs if a hairy vetch cover crop was used on the second and third corn planting date. There was a yield increase due to use of herbicide at the first corn planting date at Rock Springs in 2008, whereas the lower yield with herbicide and cover crop at the fourth planting date is considered an anomaly. Corn yields at Rock Springs in 2008 with cover crop and without herbicide were higher or no different if compared with no cover crop but with herbicide. Corn yields did not improve due to the use of herbicide at Landisville in 2008 if a hairy vetch cover crop was used at the third and fourth corn planting dates, although herbicide use caused a significant corn yield increase on the first and second planting date. At Landisville in 2008, as at Rock Springs, lowest yields were obtained when no herbicide and no cover crop were used. At Rodale in 2007, corn yields were highest at the last two planting dates, despite the late planting date for the region (Table 5). In 2008 at Rodale, corn yields did not differ between planting dates at $P < 0.05$ level but were significant at the 0.10 level. The earlier planted corn tended to yield more than the later planted corn in 2008.

DISCUSSION

Hairy vetch was consistently killed without use of herbicide by a roller-crimper when rolled and crimped at early pod set. When rolling-crimping earlier, the risk of incomplete control increased. Other research has also shown that cover crops can be controlled more successfully at the late-bloom growth stage compared with early bud or mid bloom (Ashford and Reeves, 2003; Creamer and Dabney, 2002; Hoffman et al., 1993).

The early pod-set stage was reached in the second or third week of June in Pennsylvania. This is approximately 4 to 6 wk after recommended corn planting dates and is likely to limit corn yield potential due to a reduced length of growing season and smaller accumulation of growing degree days for corn. The danger of frost damage before maturity would also increase. Further, the hairy vetch could deplete soil moisture stored in the later winter and spring and thus increase drought stress, although during the growing season the dead vetch mulch cover would conserve moisture. Vetch biomass accumulation at time of rolling-crimping varied widely. It increased with time at two sites (as expected), but not at the Rodale site. There was also a large difference in vetch biomass production between the Rock Springs/Landisville sites and the Rodale site. Two factors may have contributed to the difference. First, the vetch was established in tilled ground at the Rodale site but with no-till methods at the other sites. This may have caused faster vetch establishment in the fall at the Rodale site, better winter survival, and a heavier vetch stand in the spring. Second, higher soil organic matter

Table 5. Corn planting date† effect on weed biomass, corn population, and corn grain yield at Rodale, Pennsylvania in 2007–2008.‡

Corn planting	2007 Weed biomass	2007 Corn population	2007 Yield	2008 Weed biomass	2008 Corn population	2008 Yield
	kg ha^{-1}	1000 ha^{-1}	Mg ha^{-1}	kg ha^{-1}	1000 ha^{-1}	Mg ha^{-1}
First	7090 b	38.6 b	3.9 b	1160 b	56.3 a	8.5 a
Second	11680 c	18.7 c	2.3 b	460 a	46.8 b	8.1a
Third	2980 a	69.2 a	8.4 a	310 a	41.7 b	7.8 a
Fourth	1350 a	74.1 a	9.6 a	400 a	50.2 a	7.1 a

† Corn planting was preceded by hairy vetch rolling-crimping operations on the same day.

‡ Letters in columns indicate differences at ***P*** < 0.05 (Tukey-Kramer mean separation).

content (5–10 g kg^{-1} greater soil organic carbon content) at the Rodale site due to past compost additions, cover cropping, and more diverse crop rotations may have favored vetch growth.

Weed biomass was reduced significantly by the hairy vetch cover crop compared with no cover. Cover crop controlled annual broadleaf weeds more consistently than annual grass weeds, and had no or little effect on perennial weed density. In many cases, weed control improved as rolling-crimping and corn planting were delayed. This may have been caused by an increase in hairy vetch biomass, which would provide a greater barrier to weed germination and emergence. However, in some cases vetch that was not completely killed by the roll-crimp operation competed with weeds and thus reduced weed (and corn) growth. Main crop performance also affected weed control. At the Rodale site in 2007 a decimated corn population in the two earliest planted treatments was the main reason for poor weed control. Additionally, late planting seemed to help escape some earlier weed flushes. Climatic conditions during the corn-growing season also determined the effectiveness of weed control in this no-till organic corn system, as weed control was better in the drier summer of 2008 than in the wetter summer of 2007.

Corn yields with hairy vetch cover crops exhibited a large range. In 2007 at the Rock Springs site, the hairy vetch cover crop did not increase corn yield if no herbicide was used. Weed biomass with cover crop was 900 kg ha^{-1} (Table 4), signifying incomplete weed control by the cover crop, and significant hairy vetch regrowth was observed in the corn planted at the first two dates (Table 1). Reduced corn plant populations due to planting problems into heavy hairy vetch cover crop may have caused yield reductions as well. Corn population with cover crop was reduced from 64,000 to 57,000 plants ha^{-1} at the Rock Springs site in 2007 (P = 0.07, results not shown). In this case, the Monosem planter had difficulty planting into the heavy hairy vetch cover crop mulch that was still green. Planting into a green cover crop is part of this system because further postponing corn planting would limit yield potential even more. Another factor for yield reduction with vetch may have been insufficient N for corn planted after hairy vetch (since the no-cover plots received N fertilizer they were less likely to show N deficiency). However, in 2008 at both Rock Springs and Landisville, corn yields with cover crop but without herbicide were much improved over those obtained without cover crop and no herbicide, and similar to those obtained without cover crop but with herbicide. At the Rodale site, 7 to 10 Mg ha^{-1} corn yields were produced at all planting dates in both years except for the two earliest corn planting dates in 2007. At the two earliest planting dates in 2007, black cutworm (*Agrotis ipsilon* Hufnagel) devastated corn populations, resulting in low yields and increased weed infestations. Black cutworm feeding peaked at the second planting date and by the third and fourth dates the critical larva stage that damaged the corn had passed, resulting in higher plant populations. Weed biomass after the third and fourth planting dates was also lower compared with the first two planting dates, which improved corn yields as well.

In conclusion, it was possible to grow corn organically without tillage after rolling-crimping a hairy vetch cover crop. For best results, the vetch needed to be rolled and crimped at early pod set or later. Reasonable weed control was supplied by the vetch mulch, although not as complete as that provided by herbicides. Corn planting dates were delayed beyond recommended dates with this system, which probably reduced corn yield potential. Corn yields up to 9.6 Mg ha^{-1} were achieved with this system, without the use of herbicides, tillage, or N fertilizer (organic or inorganic). Production risk, however was increased with this no-till organic system due to late planting, planting problems, incomplete hairy vetch termination, some weed escapes, and insect attack. This is a serious problem because recent studies show that production risk in organic production using conventional tillage is already increased above that in nonorganic production (Cavigelli et al., 2008; Posner et al., 2008). However, because of labor, energy, and machinery savings, and soil and water quality and conservation benefits, additional research is needed to increase success with this system.

Table 6. Corn planting date†, cover crop, and herbicide effects on corn yield in Rock Springs (RS) and Landisville (LV), 2007–2008.‡

Corn planting date	Cover crop	Herbicide	RS 2007	RS 2008	LV 2008
			Corn grain yield, Mg ha^{-1}		
First	Yes	No	3.4 d	6.5 b	8.2 b
	Yes	Yes	4.3 c	8.2 a	10.2 a
	No	No	2.6 de	0.5 e	0.4 f
	No	Yes	6.4 ab	7.2 ab	7.7 bc
Second	Yes	No	1.7 e	7.2 ab	6.6 c
	Yes	Yes	5.2 bc	8.3 a	8.5 b
	No	No	1.4 e	0.06 e	0.6 f
	No	Yes	5.7 bc	9 a	7.1 bc
Third	Yes	No	1.1 e	7.5 ab	4.6 d
	Yes	Yes	5.4 bc	8.4 a	4.1 d
	No	No	3.2 d	0.1 e	0.1 f
	No	Yes	6 b	7.9 a	5.3 cd
Fourth	Yes	No	2.7 d	6 b	4.9 d
	Yes	Yes	5.2 bc	3.9 d	4.8 d
	No	No	3.2 d	1.3 e	2.2 e
	No	Yes	8 a	5.2 c	5.3 cd

† Corn planting date was preceded by hairy vetch rolling-crimping operations on the same day.

‡ Letters in columns indicate differences at P < 0.05 (Tukey-Kramer mean separation).

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