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Effectiveness of Herbicides for Control of Hairy Vetch (*Vicia villosa*) in Winter Wheat

William S. Curran, John M. Wallace, Steven Mirsky, and Benjamin Crockett*

A field experiment was conducted in 2009–2010 at Pennsylvania and Maryland locations, and repeated it in 2010–2011 to test the effectiveness of POST-applied herbicides at fall and spring timings on seeded hairy vetch in winter wheat. A total of 16 herbicide treatment combinations was tested that included synthetic auxins, acetolactate synthase (ALS) inhibitors, and a protoporphyrinogen oxidase inhibitor. Spring applications tended to be more effective than fall applications. Among synthetic auxins, clopyralid (105 g ae ha^{-1}) and treatments containing dicamba (140 g ae ha^{-1}) were effective at both timings, resulting in greater than 90% hairy vetch control at wheat harvest. Pyroxsulam and prosulfuron applied at 18 g ai ha^{-1} provided the most effective hairy vetch control (> 90%) at both application timings among ALS inhibitors. Spring applications of several herbicides provided moderate (> 80%) to high (> 90%) levels of hairy vetch control, including: 2,4-D amine (140 g ae ha^{-1}), mesosulfuron-methyl (15 g ai ha^{-1}), tribenuron-methyl (13 g ai ha^{-1}), and thifensulfuron/tribenuron-methyl treatments (16 and 32 g ai ha^{-1}). Winter wheat injury was evaluated, but symptoms were negligible for most treatments. Winter wheat yields declined with increasing hairy vetch biomass. Fall herbicides may be prioritized to reduce hairy vetch competition during the fall and early spring growing season. Our research has established that several synthetic auxin and ALS-inhibiting herbicides, applied POST in fall or spring, can be safely used in winter wheat to control hairy vetch in an integrated weed management program.

Nomenclature: 2,4-D amine; dicamba; clopyralid; mesosulfuron-methyl; prosulfuron; pyroxsulam; thifensulfuron; tribenuron-methyl; carfentrazone; hairy vetch, *Vicia villosa* Roth; winter wheat, *Triticum aestivum* L.

Key words: Cover crop, integrated weed management.

En localidades de Pennsylvania y Maryland, se realizó un experimento de campo en 2009–2010, y se repitió en 2010–2011, para evaluar la eficacia de herbicidas aplicados POST en el otoño y la primavera sobre *Vicia villosa* sembrado en trigo de invierno. Se evaluó un total de 16 tratamientos de combinaciones de herbicidas, los cuales incluyeron auxinas sintéticas, inhibidores de acetolactate synthase (ALS), e inhibidores de protoporphyrinogen oxidase. Las aplicaciones de primavera tendieron a ser más efectivas que de otoño. Entre las auxinas sintéticas, clopyralid (105 g ae ha^{-1}) y los tratamientos que contenían dicamba (140 g ae ha^{-1}) fueron efectivos en ambos momentos de aplicación, y resultaron en más de 90% de control de *V. villosa* al momento de la cosecha del trigo. Pyroxsulam y prosulfuron, aplicados a 18 g ai ha^{-1}, brindaron el control más efectivo de *V. villosa* (> 90%) en ambos momentos de aplicación, entre los inhibidores de ALS. Las aplicaciones en la primavera de varios herbicidas brindaron niveles de control de *V. villosa* de moderados (> 80%) a altos (> 90%), y los tratamientos incluyeron: 2,4-D amine (140 g ae ha^{-1}), mesosulfuron-methyl (15 g ai ha^{-1}), tribenuron-methyl (13 g ai ha^{-1}), y thifensulfuron/tribenuron-methyl (16 a 32 g ai ha^{-1}). El daño en el trigo de invierno fue evaluado, pero los síntomas fueron mínimos para la mayoría de los tratamientos. Los rendimientos del trigo de invierno disminuyeron con el aumento de la biomasa de *V. villosa*. Los herbicidas aplicados en el otoño podrían ser priorizados para reducir la competencia de *V. villosa* en el otoño y temprano en la primavera durante la temporada de producción. Nuestra investigación ha establecido que varios herbicidas auxinas sintéticas e inhibidores de ALS, aplicados POST en el otoño o la primavera, pueden ser usados en forma segura en trigo de invierno para controlar *V. villosa* en un programa de manejo integrado de malezas.

Integration of winter cover crops into cropping systems can provide many agronomic benefits, including improved nutrient cycling efficiency, pest suppression, soil and water quality, and cash-crop productivity (Snapp et al. 2005). In the Chesapeake Bay watershed within the mid-Atlantic United States, increasing winter cover-crop adoption may

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significantly reduce nitrate leaching to groundwater in comparison with historical levels of nutrient loss from agricultural sources (Yeo et al. 2013). This potential benefit has prompted federal and state cost-share programs to subsidize winter cover-crop establishment for participating farmers. Crop rotations that utilize a leguminous winter cover crop can also supplement N fertilizer inputs while producing crop yields comparable with conventional fertilizer-based systems and at the same time reduce N leaching up to 40% (Tonitto et al. 2006). Consequently, there is increasing producer interest in incorporating leguminous cover crops into cropping systems within the mid-Atlantic region.

Among winter-annual leguminous cover crops, hairy vetch holds considerable potential in the mid-Atlantic. It demonstrates high levels of winter hardiness in this region (Clark 2007), and can produce high levels of cover-crop dry matter, which would result in N levels that provide much of the N requirement for high-N-requiring crops such as corn (Blevins et al. 1990; Teasdale et al. 2004). Despite these agronomic benefits, incorporation of hairy vetch into cropping systems has been slowed by grower concerns related to volunteer hairy vetch in subsequent rotational crops (Clark 2007).

Hairy vetch seeds are dimorphic, containing both soft and hard seed coats (Aarssen et al. 1986). Volunteer hairy vetch is generally the result of physical dormancy due to the hard seed coat allowing seed to persist into subsequent growing seasons. Dormancy break of hard seed is associated with a shift from low to high temperatures, which commonly occurs in arable fields after tillage (Baskin and Baskin 2006). In a survey of nine commercial hairy vetch cultivars, Jacobsen et al. (2010) found the percentage of hard seed to be variable among cohorts, ranging from 1 to 21%. Consequently, a fraction of hairy vetch planted in the fall will likely persist in the seedbank and potentially interfere with crop production as a volunteer weed in subsequent phases of the rotation.

The most common scenario in which volunteer hairy vetch becomes problematic is when winter wheat or other winter annual cereals follow in the rotation. In the mid-Atlantic, winter wheat is often used as a rotation crop in corn and soybean systems. Planting winter wheat before corn (*Zea mays* L.) enables integration of leguminous winter cover crops before corn by allowing for late summer cover-crop establishment after midsummer wheat harvest. In no-till cropping systems, hairy vetch is commonly terminated with a burn-down herbicide before cash-crop planting. However, mechanical methods such as mowing and roller-crimping have also been investigated as tools for reducing herbicide inputs (Davis 2010; Teasdale and Rosecrance 2003). Volunteer hairy vetch can result from either hard seed in the seed bank or from delayed or incomplete control of hairy vetch with chemical or mechanical termination methods that may lead to additional seed bank inputs from mature plants (Mischler et al. 2010).

Chemical control of hairy vetch before cash-crop planting can be achieved with a single application of 2,4-D (Davis 2010), which is often tank mixed with glyphosate to broaden the weed-control spectrum. Several studies have investigated the integration of hairy vetch mulches and selective herbicides as a weed-suppression tactic in no-till corn and soybean [*Glycine max* (L.) Merr.] (Curran et al. 1994; Gallagher et al. 2003; Teasdale et al. 2005). In general, selective control of hairy vetch or other *Vicia* species during the crop phase of a rotation has not been investigated. A greenhouse experiment that focused on roadside and noncropland habitats showed that *Vicia* species are more sensitive to synthetic-auxin herbicides than to acetolactate synthase (ALS) inhibitors at the seedling stage (Seefeldt et al. 2007). A broad suite of herbicides is available for broadleaf weed control within winter wheat, but hairy vetch is generally not listed on herbicide labels. General recommendations for hairy vetch control have only recently been added to mid-Atlantic crop-production guides on the basis of the research presented in this paper (Curran et al. 2012).

Information on effective herbicides, application rates, and application timing for hairy vetch control in winter wheat is needed to provide producers with precise decision tools for managing volunteer hairy vetch in winter cereal production systems that seek to incorporate leguminous winter cover crops into the rotation. The objective of this study was to evaluate hairy vetch control efficacy in winter wheat with herbicides applied either in late fall or early spring at two locations in the mid-Atlantic region.

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Table 1. Dates of management practices and sampling activities for each year of the study at Rock Springs, PA (Penn State University Russell E. Larson Agricultural Research Center [RELARC]) and Beltsville, MD (Beltsville Agricultural Research Center [BARC]).

	Rock Springs, PA		Beltsville, MD	
Treatment timing	2009–2010	2010–2011	2009–2010	2010–2011
Fall events				
Fall fertilization	October 5	October 12	October 13	October 12
Hairy vetch & wheat planting	October 6	October 13	October 14	October 13
Fall herbicide	November 29	November 24	December 4	December 11
Zadoks wheat growth stage	13	12–13	na[a]	10–11
Hairy vetch growth stage	Six leaf	Two to three leaf	Three to four leaf	One leaf
Hairy vetch height (cm)	7	1–4	7	1
Spring events				
Spring fertilization	April 2	April 10	March 25	March 25
Spring herbicide	April 12	April 30	April 2	April 7
Zadoks wheat growth stage	30–31	31–33	22–28	31
Hairy vetch growth stage	Threebranch	Three to four branch	Four to eight branch	Two to five branch
Hairy vetch height (cm)	13	12	13	8
Harvest events				
Wheat & hairy vetch biomass	June 3	June 15–19	May 19–26	June 6
Wheat grain yields	July 12	July 14	July 7	July 7

[a] na, not applicable.

Materials and Methods

A field experiment was conducted in 2009–2010 and repeated in 2010–2011 at the Penn State University Russell E. Larson Agricultural Research Center (RELARC) near Rock Springs, PA (40.73°N, 77.05°W) and at the U.S. Department of Agriculture (USDA) Beltsville Agricultural Research Center (BARC) near Beltsville, MD (39.03°N, 75.58°W) to test the effectiveness of selective herbicides and two application timings (fall vs. spring) on hairy vetch control in winter wheat. The soil at the RELARC was a Hagerstown silt loam (fine mixed, semiactive mesic Typic Hapludalfs), a well-drained productive soil common to Pennsylvania. The soil at Beltsville consisted of Codorus and Hatboro fine loam (fine-loamy, mixed, active, mesic Fluvaquentic Dystrudepts).

In early October of both experimental cycles, hairy vetch (AU Early Cover cultivar; Mosjidis et al. 1995) was seeded at a 2.5-cm depth into a tilled seedbed in 25-cm rows at 11 kg ha^{-1} with a Great Plains no-till drill (Great Plains, Salina, KS 67401) at BARC and with a Tye no-till drill (AGCO, Duluth, GA 30096) at RELARC (Table 1). Immediately after hairy vetch planting, winter wheat (Growmark FS 627) was seeded at a 3.2-cm depth in 19-cm rows at 135 kg ha^{-1}. Nitrogen fertilizer was applied and incorporated at a rate of 34 kg ha^{-1} before planting, and was followed with 67 kg ha^{-1} top-dressed N at spring green-up.

Treatments included common herbicides utilized for broadleaf weed control in winter wheat production in the mid-Atlantic region, including: (1) synthetic auxins (group 4), (2) ALS inhibitors (group 2), (3) a protoporphyrinogen oxidase (PPO) inhibitor (group 14), and (4) combinations of synthetic auxins, ALS inhibitors, or synthetic auxins + ALS inhibitors (Table 2). Herbicide treatments were applied at mid-label rates using either a POST fall or spring application timing (Table 1). Hairy vetch ranged from the one- to six-leaf stage at the fall application timing and from two- to eight-branch stage at the spring application timing. Herbicides were applied with a handheld CO_2 backpack sprayer calibrated to deliver 187 L ha^{-1} at 207 kPa and included appropriate adjuvants as specified by product labels. Experiments were arranged as randomized complete blocks with four replications and individual plot size measured 3 by 9 m. Two nontreated controls per replication were included for treatment comparisons.

Hairy vetch control was assessed visually on a scale of 0 to 100% (0 = no control and 100 = complete control) in each plot in the spring and

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Table 2. Summary of herbicide treatments applied at both fall and spring timings at Rock Springs, PA (Penn State University Russell E. Larson Agricultural Research Center [RELARC]) and Beltsville, MD (Beltsville Agricultural Research Center [BARC]).

Herbicide treatment[a]	Application rate
Synthetic auxin	g ai ha^{-1}
2,4-D amine[b]	70
2,4-D amine	140
Dicamba	140
2,4-D amine + dicamba	140 + 140
MCPA amine[b]	70
MCPA amine[b]	140
Clopyralid	105
Acetolactate synthase (ALS) inhibitor	
Thifensulfuron	26
Tribenuron	13
Thifensulfuron/tribenuron	16
Thifensulfuron/tribenuron	32
Mesosulfuron-methyl	15
Prosulfuron[c]	18
Pyroxsulam[c]	18
Protoporphyrinogen oxidase (PPO)inhibitor	
Carfentrazone[c]	17
Two mechanisms of action	
Thifensulfuron/tribenuron + 2,4-D amine	16 + 70

[a] ALS and PPO inhibitor herbicide treatments include nonionic surfactant (0.25% v/v) and ammonium sulfate at 2.24 kg ha^{-1}.

[b] Herbicide treatments applied only in 2009–2010 experiments.

[c] Herbicide treatments not applied in 2009–2010 experiment at Rock Springs, PA (RELARC) because of weather conditions at fall application timing.

before winter wheat harvest in midsummer. Visual evaluations of winter wheat injury (0 to 100%) were conducted approximately 1 and 2 mo after treatment for both application timings. In addition, hairy vetch and winter wheat aboveground biomass was collected from a 0.5- by 1.0-m quadrat just before winter wheat harvest. At full maturity, wheat grain was harvested with a small-plot combine at each site (ALMACO [Nevada, IA 50201] at BARC and Wintersteiger [WINTERSTEIGER AG, Ried, Austria] at RELARC). Wheat grain and vetch seed were separated using a gravity-driven spiral separator designed to separate seeds of different shapes in 2009–2010 experiments. Separated wheat and vetch seed were weighed to quantify hairy vetch seed contamination of the harvested wheat. Test weight and moisture of the wheat were measured using a Dickey–John Model GAC 2100 Grain Analysis Computer (Dickey–John Corporation, Springfield, IL 62629).

Statistical Analysis. To ensure uniformity across experimental sites, the statistical analysis was limited to herbicide treatment effects on hairy vetch control and winter wheat injury to biomass metrics. Hairy vetch control (%) is evaluated using the equation:

$$(1 - [\text{treatment}/\text{nontreated control}]) \times 100 \quad [1]$$

where hairy vetch control (%) level is quantified as the ratio of hairy vetch biomass (g m^{-2}) within a given treatment plot and replicate to hairy vetch biomass in the nontreated control plots averaged within replicates. Winter wheat yields (kg ha^{-1}) were utilized to determine the total effect of herbicide treatments on winter wheat production. This included potential winter wheat injury as a direct result of herbicide applications and the potential competitive suppression or release that may result from low or high levels of hairy vetch control. ANOVA was conducted on hairy vetch control, winter wheat yields, and hairy vetch seed contamination using the MIXED procedure in SAS 9.3 (SAS Institute Inc., Cary, NC 27513). We first evaluated models that considered herbicide, application timing, site, year, and the interaction among these terms as a fixed effect. No site-year-by-treatment interaction was observed. Consequently, site and year were included in models as random effects. Hairy vetch control data, expressed as a percentage in comparison with the nontreated control, were arcsine transformed to meet assumptions of normality before ANOVA. Back-transformed means and standard errors are presented in figures. Wheat yield and hairy vetch seed contamination data (kg ha^{-1}) met assumptions of normality and were analyzed using a Gaussian distribution. Hairy vetch control, winter wheat yield, and hairy vetch seed contamination means were compared with the use of Fisher's LSD at a $P < 0.05$ significance level.

Winter wheat yield data at BARC in 2009–2010 and hairy vetch control data at BARC in 2010–2011 were precluded from analysis because of geese (*Branta canadensis*) herbivory and establishment failures, respectively. Consequently, hairy vetch control and winter wheat yield data were each evaluated across 3 site-years. In 2009–2010, weather conditions prevented the application of prosulfuron, pyroxsulam, and carfentrazone-ethyl in the

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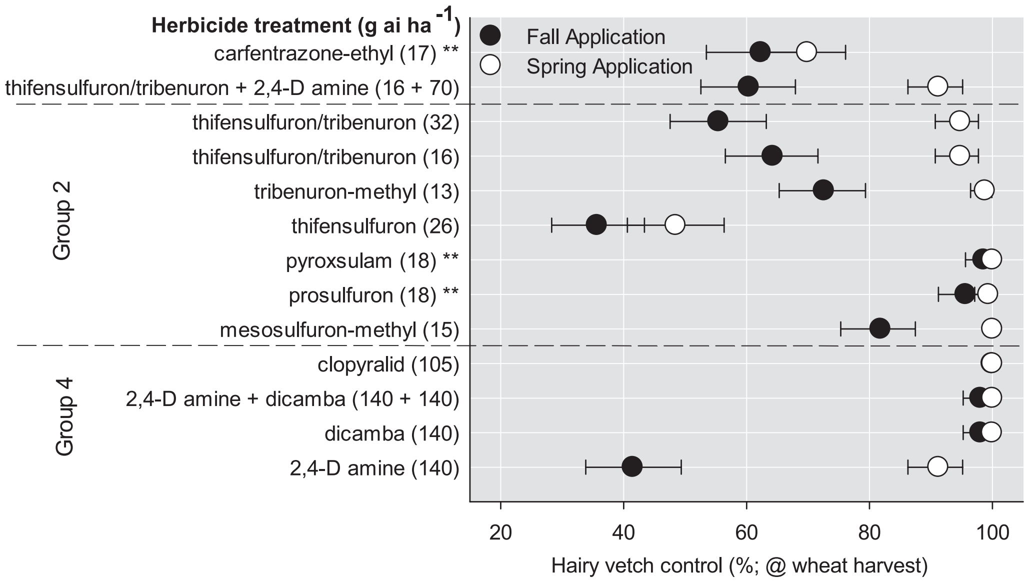

Figure 1. Effect of herbicide treatment and application timing on hairy vetch control relative to the untreated control at winter wheat harvest. Treatment means with overlapping standard errors are not significantly different (Fisher's LSD $P < 0.05$). Data are pooled across sites and years. Synthetic auxin (group 4) and ALS inhibitor (group 2) herbicides are grouped for presentation. Treatments followed by asterisks (**) occurred in only 2 of 3 site-years and cannot be included in pair-wise comparisons with other herbicide treatments (no asterisk).

RELARC experiment at the fall application timing. Consequently, these three treatments were analyzed using 2 site-years (Table 2). Three herbicide treatments included in the 2009–2010 experiments resulted in poor hairy vetch control and were removed from the 2010–2011 experiments (Table 2). These herbicide treatments are precluded from pair-wise comparisons with other herbicide treatments. Rather, we limit our analysis of these treatments to reporting hairy vetch control estimates for the 2009–2010 experiments across study locations. Finally, analysis of hairy vetch seed contamination was limited to the 2009–2010 experiments.

To determine the effect of hairy vetch control at either the fall or spring application timing on winter wheat yields, we regressed plot-level wheat yields (kg ha^{-1}) as a function of final hairy vetch biomass (kg ha^{-1}) and application timing using regression procedures in SAS 9.3. Herbicide treatments that resulted in poor hairy vetch control in 2009–2010 experiments produced a broad range of final hairy vetch biomass values to evaluate hairy vetch biomass and wheat yield relationships. The exclusion of these herbicides in the 2010–2011 experiment resulted in a narrower range of hairy vetch biomass values. Consequently, regression analysis was limited to the 2009–2010 experiments at BARC and RELARC. For each site, we constructed *F*-tests to test the null hypotheses: (1) the difference between fall and spring application regression slopes is equal to zero, and (2) the difference between fall and spring regression lines (intercept + slope) is equal to zero.

Results and Discussion

Hairy Vetch Control. Hairy vetch control varied on the basis of both herbicide treatments and application timing and there was a significant herbicide treatment-by-application timing effect ($P = 0.0002$; Figure 1). Among synthetic auxins (group 4), hairy vetch control was similarly high ($> 90\%$) after clopyralid, dicamba, or dicamba + 2,4-D amine applied as either a fall or spring POST application. These herbicides were consistently effective for control of hairy vetch. A spring application of 2,4-D amine at 140 g ha^{-1} resulted in better hairy vetch control (91%) compared with the fall application (41%). In 2009–2010, 2,4-D amine was also evaluated at a lower rate (70 g ha^{-1}), which resulted in less than 75% hairy vetch control at both application timings. Subsequent field studies suggest that ester formulations of 2,4-D provide

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consistently higher levels of hairy vetch control across fall and spring application timings than amine formulations applied at comparable rates (Curran, personal communication). In 2009–2010, MCPA was also included at two application rates (70 and 140 g ha^{-1}). Fall application of MCPA provided only 35 to 44% hairy vetch control, whereas spring applications provided 59% control at the 70 g ha^{-1} application rate and 82% control at the 140 g ha^{-1} rate.

With the exception of thifensulfuron applied alone, spring applications of ALS inhibitors (group 2) resulted in high (> 90%) levels of hairy vetch control (Figure 1). Hairy vetch control after fall applications of ALS inhibitors was variable. Fall applications of prosulfuron and pyroxsulam resulted in at least 95% control and were comparable with control levels observed with these herbicides at the spring timing. Fall application of mesosulfuron-methyl, thifensulfuron, tribenuron-methyl, and thifensulfuron/tribenuron-methyl resulted in less than 75% hairy vetch control. Both fall and spring applications of thifensulfuron applied alone resulted in poor (< 55%) hairy vetch control. These results indicate that hairy vetch control with thifensulfuron/tribenuron-methyl is a function of tribenuron-methyl efficacy, which did not differ from the thifensulfuron/tribenuron-methyl treatment combination when applied alone. Moreover, the addition of 2,4-D amine at 140 g ha^{-1} to the thifensulfuron/tribenuron treatment combination did not improve hairy vetch control at either timing, and did not differ from the application of tribenuron-methyl alone. Fall and spring applications of the PPO inhibitor carfentrazone-ethyl resulted in similar results, providing less than 75% control of hairy vetch (Figure 1).

Winter Wheat Injury and Yield. Visual wheat injury was negligible (0 to 4%) across treatments and application timings at both evaluation dates (1 and 2 mo after application), with the exception of the spring application of 2,4-D amine (14%). These observations are consistent with expected levels of injury for herbicide products that have adequate crop safety for weed management in cereal grains (McNaughton et al. 2014; Robinson et al. 2013; Soltani et al. 2006). Unacceptable levels of wheat injury (9 to 14% wheat yield reductions) have previously been reported after POST fall applications of 2,4-D, using both amine and ester formulations (Soltani et al. 2006). In general, winter wheat injury is more likely to be observed when herbicides are applied in spring using higher labeled rates (Derksen et al. 1989).

A significant herbicide treatment-by-application timing effect ($P = 0.0019$) occurred with winter wheat yields (Figure 2). Treatments containing tribenuron-methyl or thifensulfuron/tribenuron-methyl resulted in greater wheat yields (477 to 719 kg ha^{-1}) after spring applications in comparison with fall applications. The increase in wheat yields after spring applications can be attributed to the significantly greater hairy vetch control in comparison with fall applications (Figure 1). Comparatively greater wheat yields (1,050 kg ha^{-1}) were also observed in spring applications of 2,4-D amine applied alone, which was also related to better hairy vetch control at the spring application timing. This same trend, though not significant, was also detected with mesosulfuron-methyl. In contrast, winter wheat yields were higher with fall applications of pyroxsulam, prosulfuron, and dicamba in comparison with spring applications, and this same trend was observed with clopyralid and 2,4-D amine + dicamba treatments (Figure 2). In each of these treatments, hairy vetch control efficacy was comparable among application timings, which suggests that hairy vetch growth in the fall and early spring has the potential to reduce winter wheat yields if hairy vetch control applications are delayed until spring. This trend is consistent with previous research that has emphasized the potential for wheat yield loss due to weed competition during the autumn and early spring growing season (Blackshaw and Hamman 1998; Geier et al. 2002, 2011; Stougaard et al. 2004).

Wheat grain yield (kg ha^{-1}) was expressed as a function of hairy vetch dry matter (kg ha^{-1}) at harvest (Figure 3) and quantified hairy vetch seed contamination as a percentage of wheat grain yield for the 2009–2010 experiments at RELARC and BARC (Table 3). Wheat yields at BARC were generally lower across treated plots in comparison with RELARC because of poor stand establishment. This resulted in considerably more hairy vetch in plots with poor control than in plots with good control. However, similar relationships between wheat yield and hairy vetch biomass were observed between study sites. Winter wheat yields declined

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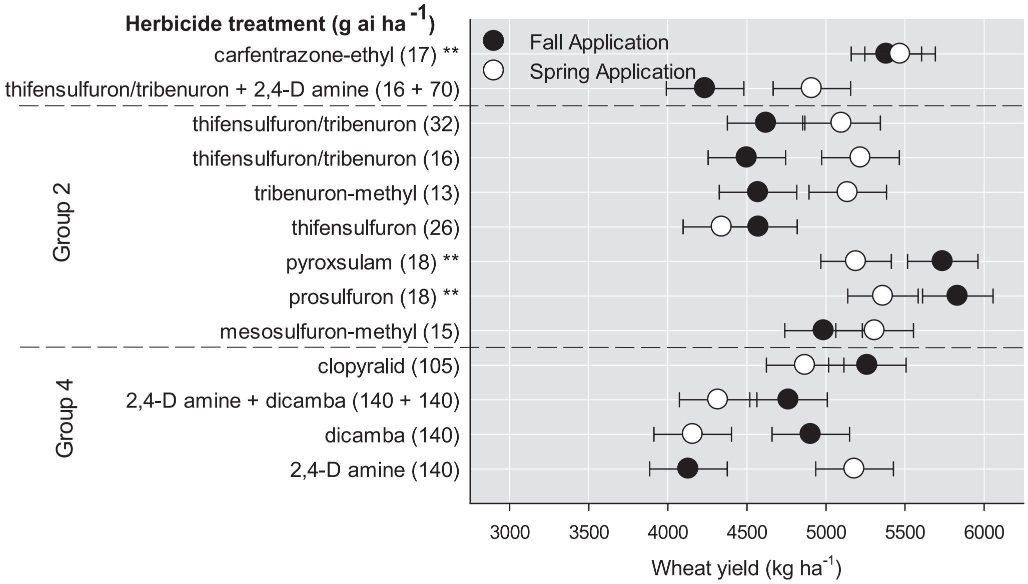

Figure 2. Effect of herbicide treatment and application timing on winter wheat yields relative to the untreated control. Treatment means with overlapping standard errors are not significantly different (Fisher's LSD $P < 0.05$). Data are pooled across sites and years. Synthetic auxin (group 4) and ALS inhibitor (group 2) herbicides are grouped for presentation. Treatments followed by asterisks (**) occurred in only 2 of 3 site-years and cannot be included in pair-wise comparisons with other herbicide treatments (no asterisk).

0.55 to 1.2 kg ha^{-1} per 1 kg ha^{-1} increase in hairy vetch biomass.

Hairy vetch seed contamination in winter wheat grain ranged from 4 to 656 kg ha^{-1} across herbicide treatments (Table 3). Fall-applied herbicide treatments of 2,4-D amine, thifensulfuron, thifensulfuron/tribenuron + 2,4-D amine, and carfentrazone resulted in hairy vetch seed contamination levels that were comparable with the untreated check. All spring herbicide applications, with the exception of thifensulfuron and carfentrazone, significantly decreased hairy vetch seed contamination in comparison with the untreated check. Synthetic auxin (dicamba, 2,4-D amine + dicamba, and clopyralid) and ALS inhibitor (mesosulfuron-methyl, prosulfuron, and pyroxsulam) herbicides that resulted in moderate to high (80 to 99%) levels of hairy vetch control at both application timings also resulted in less hairy vetch seed contamination in comparison with the nontreated control. We observed a general trend of higher seed contamination levels at the fall application timing, suggesting that uncontrolled plants are less likely to produce mature seed after spring-timed applications in comparison with the fall application timing.

Summary. Hairy vetch control efforts are likely to be integrated into a weed control program that accounts for other weed species and crop rotation considerations. This underscores the importance of developing herbicide control options that may be utilized for hairy vetch control in the fall or spring depending on management priorities. Our research has established that several synthetic auxin and ALS inhibitor herbicides, applied POST in fall or spring, can be safely used in winter wheat to control hairy vetch. This research also shows that some members of these herbicide families are not very effective for control of hairy vetch in winter wheat. Among synthetic auxins, clopyralid provided the most consistent control of hairy vetch at both application timings. Clopyralid controls several winter annual and perennial weed species that are common within mid-Atlantic production systems, most notably horseweed (*Conyza canadensis* L.) and Canada thistle (*Cirsium arvense* L.). Dicamba applied alone or in combination with 2,4-D amine also provided consistent hairy vetch control at both application timings. The application rates we tested resulted in negligible winter wheat injury, but both clopyralid (Derksen et al. 1989) and dicamba (Tottman 1978) may result in wheat yield loss due to injury if used at higher application rates. Among ALS inhibitors, pyroxsulam and prosulfuron provided the most consistent control of hairy vetch at both application timings. Pyroxsulam is often utilized in winter

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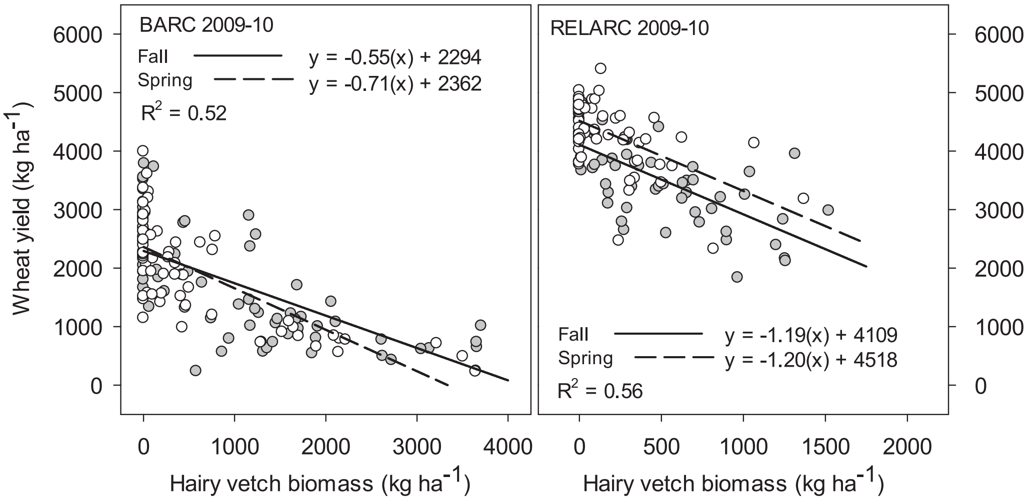

Figure 3. Linear relationship between winter wheat grain yields (kg ha^{-1}) and hairy vetch biomass (kg ha^{-1}) after fall and spring herbicide application treatments targeting hairy vetch control in the 2009–2010 experiments at Beltsville, MD (Beltsville Agricultural Research Center [BARC]) and Rock Springs, PA (Penn State University Russell E. Larson Agricultural Research Center [RELARC]). The relationship between wheat yield and hairy vetch biomass was significantly influenced by application timing at the RELARC location ($df = 2$, $F = 7.77$, $P = 0.0007$), but did not differ at the BARC location ($df = 2$ $F = 1.11$, $P = 0.33$).

wheat production for downy brome (*Bromus tectorum* L.) control (Geier et al. 2011), a winter annual grass that is becoming increasingly problematic in fall-seeded crops within the mid-Atlantic. Prosulfuron provides effective control of winter annual mustard species when applied in fall, and can be used as a PRE treatment to control common ragweed (*Ambrosia artemisiifolia* L.) in spring-seeded cereal grains (Soltani et al. 2014). Several herbicides provide moderate ($> 80\%$) levels of hairy vetch control and acceptable levels of crop safety when utilized at the spring application

Table 3. Herbicide treatment and application timing (fall and spring) effect on hairy vetch seed production (kg ha^{-1}) in 2009–2010 experiments.

		Hairy vetch seed yield	
Herbicide treatment[a]	Rate	Fall application	Spring application
	g ai ha^{-1}	kg ha^{-1}	
Nontreated check	0	453	455
2,4-D amine	140	468	149
Dicamba	140	188	10
2,4-D amine + dicamba	140 + 140	81	10
Clopyralid	105	4	6
Mesosulfuron-methyl	15	184	10
Prosulfuron**	18	67	12
Pyroxsulam**	18	15	7
Thifensulfuron	26	463	442
Tribenuron-methyl	13	367	89
Thifensulfuron/tribenuron	16	352	263
Thifensulfuron/tribenuron	32	315	98
Thifensulfuron/tribenuron + 2,4-D amine	16 + 70	466	272
Carfentrazone**	17	656	522
$LSD_{(0.05)}$		67	

[a] Herbicide treatments followed by asterisks (**) were not applied in 2009–2010 experiment at Rock Springs, PA (Penn State University Russell E. Larson Agricultural Research Center).

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timing, including tribenuron-methyl, thifensulfuron/tribenuron-methyl, and thifensulfuron/tribenuron-methyl + 2,4-D amine. In total, these herbicides provide several options for targeting volunteer hairy vetch control in a variety of cropping systems and weed communities.

Finally, field monitoring should be considered a critical component of an integrative weed management program for hairy vetch control to maximize the effectiveness of herbicide control strategies. If hairy vetch is identified at the seedling emergence stage, fall applications may help to prevent wheat yield loss due to hairy vetch competition in the autumn and early spring growing season. In separate research at our study sites, simulated inversion tillage significantly reduced hairy vetch seedling emergence and increased seed bank loss in comparison with a shallow-placed seed bank (Wallace et al. 2014). Cultural control strategies, such as targeted tillage events, may be used in combination with effective herbicides and application timings to manage volunteer hairy vetch in winter cereal grains so that the positive cover-crop benefits of hairy vetch may be realized in mid-Atlantic cropping systems.

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Literature Cited

Aarssen LW, Hall IV, Jensen K (1986) The biology of Canadian weeds. 76. *Vicia angustifolia* L., *V. cracca* L., *V. sativa* L., *V. tetrasperma* (L.) Schreb and *V. villosa* Roth. Can J Plant Sci 66:711–737

Baskin CC, Baskin JM (2006) The natural history of soil seed banks of arable land. Weed Sci 54:549–557

Blackshaw RE, Hamman WH (1998) Control of downy brome (*Bromus tectorum*) in winter wheat (*Triticum aestivum*) with MON 37500. Weed Technol 12:421–425

Blevins RL, Herbek JH, Frye WW (1990) Legume cover crops as a nitrogen source for no-till corn and grain sorghum. Agron J 82:769–772

Clark A, ed (2007) Managing Cover Crops Profitably. 3rd edn. Sustainable Agriculture Network Handbook Series 9. Beltsville, MD: Sustainable Agriculture Network

Curran WS, Hoffman LD, Werner EL (1994) The influence of a hairy vetch (*Vicia villosa*) cover crop on weed control in corn (*Zea mays*). Weed Technol 8:777–784

Curran WS, Lingenfelter DD, Tooker JF (2012). Small grains pest management. Pages 313–331 *in* Penn State Agronomy Guide. University Park, PA: College of Agricultural Sciences, The Pennsylvania State University

Davis AS (2010) Cover-crop roller-crimper contributes to weed management in no-till soybean. Weed Sci 58:300–309

Derksen DA, Kirkland KJ, McLennan BR, Hunter JH, Loeppky HA, Bowren KE (1989) Influence of fall and spring herbicide application on winter wheat (*Triticum aestivum* L. 'Norstar'). Can J Plant Sci 69:881–888

Gallagher RS, Cardina J, Loux M (2003) Integration of cover crops with postemergence herbicides in no-till corn and soybean. Weed Sci 51:995–1001

Geier P, Stahlman PW, Peterson DE, Miller SD (2002) Application timing effects BAY MKH 6561 and MON 37500 efficacy and crop response in wheat. Weed Technol 16:800–806

Geier PW, Stahlman PW, Peterson DE, Claassen MM (2011) Pyroxsulam compared with competitive standards for efficacy in winter wheat. Weed Technol 25:316–321

Jacobsen KL, Gallagher RS, Burnham M, Bradley BB, Larson ZM, Walker CW, Watson CJ (2010) Mitigation of seed germination impediments in hairy vetch. Agron J 102:1346–1351

McNaughton KE, Brown LR, Sikkema PH (2014) Tolerance of winter wheat (*Triticum aestivum* L.) and underseeded red clover (*Trifolium pretense* L.) to fall-applied post-emergent broadleaf herbicides. Am J Plant Sci 5:1265–1271

Mischler RD, Duiker SW, Curran WS, Wilson D (2010) Hairy vetch management for no-till organic corn production. Agron J 102:355–362

Mosjidis JA, Owsley CM, Lirkland MS, Rogers KM (1995) Registration 'AU Early Cover' hairy vetch. Crop Sci 35:1509

Robinson MA, Cowbrough MJ, Sikkema PH, Tardif FJ (2013) Winter wheat (*Triticum aestivum* L.) tolerance to mixtures of herbicides and fungicides applied at different timings. Can J Plant Sci 93:491–501

Seefeldt SS, Conn JS, Jackson BE, Sparrow SD (2007) Response of seedling bird vetch (*Vicia cracca*) to six herbicides. Weed Technol 21:692–694

Snapp SS, Swinton SM, Labarta R, Mutch D, Black JR, Leep R, Nyiraneza J, O'Neil K (2005) Evaluating cover crops for benefits, costs and performance within cropping system niches. Agron J 97:322–332

Soltani N, Brown LR, Cowan T, Sikkema PH (2014) Weed management in spring seeded barley, oats and wheat with prosulfuron. Int J Agron DOI: 10.1155/2014/950923

Soltani N, Shropshire C, Sikkema PH (2006) Responses of winter wheat (*Triticum aestivum* L.) to autumn applied post-emergence herbicides. Crop Prot 25:346–349

Stougaard RN, Mallory-Smith CA, Mickelson JA (2004) Downy brome (*Bromus tectorum*) response to imazamox rate and application timing in herbicide-resistant winter wheat. Weed Technol 23:202–205

Teasdale JR, Devine TE, Mosjidis JA, Bellinder RR, Beste CE (2004) Growth and development of hairy vetch cultivars in the

https://doi.org/10.1614/WT-D-14-00139.1 Published online by Cambridge University Press

northeastern United States as influenced by planting and harvesting date. Agron J 96:1266–1271

Teasdale JR, Pillai P, Collins RT (2005) Synergism between cover crop residue and herbicide activity on emergence and early growth of weeds. Weed Sci 53:521–527

Teasdale JR, Rosecrance RC (2003) Mechanical versus herbicidal strategies for killing a hairy vetch cover crop and controlling weeds in minimum-tillage corn production. Am J Alt Agric 18:95–102

Tonitto C, David MB, Drinkwater LE (2006) Replacing bare fallows with cover crops in fertilizer-intensive cropping systems: a meta-analysis of crop yield and N dynamics. Agric Ecosyst Environ 112:58–72

Tottman DR (1978) The effects of a dicamba herbicide mixture on the grain yield components of winter wheat. Weed Res 18:335–339

Wallace JM, Mirsky S, Curran WS, Crockett (2014) Hairy vetch (*Vicia villosa*) seedbank dynamics and implications for cover crop management. Proc Northeast Weed Sci Soc 69

Yeo IY, Lee S, Sadeghi AM, Beeson PC, Hively WD, McCarty GW, Lang MW (2013) Assessing winter cover crop nutrient uptake efficiency using a water quality simulation model. Hydrol Earth Syst Sci Discuss 10:14229–14263

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