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Integrated Weed Management Strategies in Cover Crop–based, Organic Rotational No-Till Corn and Soybean in the Mid-Atlantic Region

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Cover crop–based, organic rotational no-till (CCORNT) corn and soybean systems have been developed in the mid-Atlantic region to build soil health, increase management flexibility, and reduce labor. In this system, a roller-crimped cover crop mulch provides within-season weed suppression in no-till corn and soybean. A cropping system experiment was conducted in Pennsylvania, Maryland, and Delaware to test the cumulative effects of a multitactic weed management approach in a 3-yr hairy vetch/triticale–corn–cereal rye–soybean–winter wheat CCORNT rotation. Treatments included delayed planting dates (early, intermediate, late) and supplemental weed control using high-residue (HR) cultivation in no-till corn and soybean phases. In the no-till corn phase, HR cultivation decreased weed biomass relative to the uncultivated control by 58%, 23%, and 62% in Delaware, Maryland, and Pennsylvania, respectively. In the no-till soybean phase, HR cultivation decreased weed biomass relative to the uncultivated treatment planted in narrow rows (19 to 38 cm) by 20%, 41%, and 78% in Delaware, Maryland, and Pennsylvania, respectively. Common ragweed was more dominant in soybean (39% of total biomass) compared with corn (10% of total biomass), whereas giant foxtail and smooth pigweed were more dominant in corn, comprising 46% and 22% of total biomass, respectively. Common ragweed became less abundant as corn and soybean planting dates were delayed, whereas giant foxtail and smooth pigweed increased as a percentage of total biomass as planting dates were delayed. At the Pennsylvania location, inconsistent termination of cover crops with the roller-crimper resulted in volunteer cover crops in other phases of the rotation. Our results indicate that HR cultivation is necessary to achieve adequate weed control in CCORNT systems. Integration of winter grain or perennial forages into CCORNT systems will also be an important management tactic for truncating weed seedbank population increases.
Nomenclature: Common ragweed, *Ambrosia artemisiifolia* L.; giant foxtail, *Setaria faberi* Herrm.; smooth pigweed, *Amaranthus hybridus* L.; cereal rye, *Secale cereale* L.; hairy vetch, *Vicia villosa* Roth; triticale, × *Triticosecale* Wittm. ex A. Camus [*Secale* × *Triticum*]; corn, *Zea mays* L.; soybean, *Glycine max* (L.) Merr.; winter wheat, *Triticum aestivum* L.
Key words: Cover crops, cropping system, high-residue cultivation, organic rotational no-till, organic transition, roller-crimper, reduced tillage.

Organic growers are interested in using cover crops to reduce tillage and improve soil health (Jerkins and Ory 2016). Reduced-tillage practices offer the potential for fuel and labor savings compared with tillage and cultivation practices that are typically employed in organic annual grain production systems (Mirsky et al. 2012). However, reduced-tillage practices that focus on improving soil health have the potential to inhibit integrated weed management options (Smith et al. 2011c). Weed control is a persistent challenge in organic crop production, and reducing the intensity or frequency of primary tillage further limits weed control tactics available to organic growers.

Research in the mid-Atlantic region has focused on developing cover crop–based, organic rotational no-till (CCORNT) corn and soybean production systems (Mirsky et al. 2012, 2013; Wallace et al. 2017). The CCORNT approach is characterized by no-till planting summer annual cash crops into mulch

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from fall-seeded cover crops that are mechanically terminated with a roller-crimper. Similar organic no-till production practices that use roller-crimped cover crops have been investigated for grain and vegetable systems in various production regions (Clark et al. 2017; Delate et al. 2012; Halde et al. 2017; Reberg-Horton et al. 2012). In the mid-Atlantic region, the primary cover crops used in CCORNT systems are cereal rye before soybean and hairy vetch/ winter cereal cover crop mixtures before corn.

In addition to shading weeds in the fall and early spring while cover crops are actively growing, rolled cover crop mulches provide within-season weed suppression in corn and soybean. Cover crop mulches suppress summer annual weeds by: (1) attenuation of germination cues via changes in light quality, soil temperature, and soil moisture at the soil surface (Teasdale and Mohler 1993); and (2) physical interference of surface mulches with seedling recruitment, leading to exhaustion of nutrient reserves prior to seedling establishment (Teasdale and Mohler 2000). Some cover crops, including cereal rye, release phytotoxic compounds that suppress potential competitors, but recent research suggests that weed suppression from allelopathic compounds in cereal rye is highly variable and likely plays only a minor role in weed suppression relative to physical mechanisms (Reberg-Horton et al. 2005; Rice et al. 2012; Teasdale et al. 2012b). Roller-crimped cereal rye can also immobilize high levels of soil inorganic nitrogen, which has been shown to lower weed interference with no-till soybean as a result of limited nitrogen availability to weed populations (Wells et al. 2013).

Maximizing cover crop biomass prior to termination has been a primary weed management objective in CCORNT systems, given that greater biomass increases weed suppression (Ryan et al. 2011). Management practices that can lead to higher cereal rye biomass levels in no-till soybean systems include lengthening the cereal rye growing season via earlier planting or delayed termination (Mirsky et al. 2011; Mischler et al. 2010a; Nord et al. 2011). Delayed termination and increased seeding rates have also been shown to increase hairy vetch biomass accumulation prior to termination (Mirsky et al. 2017a; Mischler et al. 2010b). The timing of cover crop termination and soil disturbance at cash crop planting may also act as important management filters in CCORNT systems that select for or against weed species (Booth and Swanton 2002). Recent studies have demonstrated that the timing of cover crop termination can select for weed species based on emergence periodicity traits in both organic no-till corn (Teasdale and Mirsky 2015) and soybean (Nord et al. 2012).

To optimize CCORNT systems, previous research has focused on identifying cover crop biomass thresholds that consistently result in adequate levels of weed suppression in organic no-till systems (Mischler et al. 2010a; Nord et al. 2011; Smith et al. 2011b). However, weed-suppressive thresholds differ across the mid-Atlantic region (Liebert et al. 2017; Nord et al. 2011; Smith et al. 2011), and narrow growing season windows or weather that interferes with timely field operations can result in cover crop biomass accumulation below targeted thresholds. Consequently, multitactic weed management approaches are necessary to ensure the viability of CCORNT systems.

Supplemental high-residue, interrow cultivation (hereafter HR cultivation) has been tested in cover crop–based, no-till corn (Keene and Curran 2016; Teasdale et al. 2012a; Zinati et al. 2017) and soybean (Liebert et al. 2017; Nord et al. 2012; Zinati et al. 2017). In general, these studies indicate that HR cultivation routinely reduces total in-season weed biomass, thereby decreasing weed interference with the cash crop. The primary benefit of integrating HR cultivation is better control of weed species that are less sensitive to cover crop mulches. High-residue cultivators are equipped with a single, wide sweep (55 cm) that is set 3- to 7-cm below the soil surface, resulting in minimal soil disturbance. High-residue cultivator sweeps separate the roots of weeds from the aboveground portion of the plant and thus are effective on weeds after they have established. HR cultivation controls summer annual weeds that emerge prior to cover crop termination, such as common ragweed, and survive in surface mulch (Liebert et al. 2017; Nord et al. 2011).

We conducted a 3-yr cropping systems experiment at three mid-Atlantic locations to evaluate the effects of integrating cultural and mechanical weed management tactics in a CCORNT system using a corn–soybean–winter wheat rotation. We evaluated delayed cash crop planting in the corn and soybean phase with and without the use of supplemental HR cultivation. In soybean, we included an additional cultural weed control tactic of narrower crop spacing (19-or 38-cm rows, depending on location) when HR cultivation was not employed. To our knowledge, this experiment is the first to test the cumulative effects of CCORNT weed management practices within a crop rotation. Delaying cash crop planting as a cultural weed management practice can produce several agronomic trade-offs that may influence the viability of CCORNT systems. Consequently, we investigated the effects of delayed cash crop planting on cover crop termination efficacy and volunteer cover crop legacies (Keene et al. 2016), regulation of early-season insect pests by beneficial arthropods (Rivers et al. 2016), and cash crop performance (Wallace et al. 2017). In this paper, we report the effects of alternative multitactic weed management strategies on within-season weed control, species-level responses, and weed community shifts in CCORNT systems across the mid-Atlantic region.

Materials and Methods

Study Location. The cropping system study was conducted between 2011 and 2013 at three locations in the mid-Atlantic region of the United States. The most southern location was at the University of Delaware's Carvel Research and Education Center located near Georgetown, DE (hereafter DE). The DE experiment was on Pepperbox loamy sand (loamy, mixed, semiactive, mesic Aquic Arenic Paleudults), Klej loamy sand (mesic, coated Aquic Quartzipsamments), and Hurlock loamy sand (coarse-loamy, siliceous, semiactive, mesic Typic Endoaquults) soils. The study was also established at the U.S. Department of Agriculture Agricultural Research Service Beltsville Agricultural Research Center in Beltsville, MD (hereafter MD) on Codorus silt loam (fine-loamy, mixed, active, mesic Fluvaquentic Dystrudepts) soils. The most northern location was the Penn State Russell E. Larson Agricultural Experiment Center at Rock Springs, PA (hereafter PA). The PA site was dominated by Hagerstown silt loam soils (fine, mixed, semiactive, mesic Typic Hapludalfs) with a small amount of shallower Opequon-Hagerstown (clayey, mixed, active, mesic Lithic Hapludalfs) soils. Across study locations, the climate is considered temperate humid, but growing season length varies, ranging from 2,040 to 2,110 growing degree days (GDD) in DE and MD, respectively, to 1,570 GDD in PA from April to October. Research plots were in transition from conventional to certified organic production during the 3 yr of the study.

Experimental Design. The cropping system study followed a 3-yr corn–soybean–winter wheat rotation with a hairy vetch/triticale cover crop mixture preceding corn and a cereal rye cover crop preceding soybean. The experimental design was a randomized complete block, split-split-plot design with four replications at each site. Each block consisted of three main plots planted to corn (C), soybean (S), or wheat (W) in a full-entry design, which allows for the presence of each cash crop in each year of the 3-yr rotation (C–S–W, S–W–C, W–C–S). Main plots measured 110-m long by 18-m wide at MD and PA, and 110-m long by 15-m wide at DE.

Weed management treatments were imposed in split-split plots within the main plots planted to corn and soybean each year. Weed management in wheat was the same across systems. Split-plot treatments included three cash crop planting dates, referred to as early, intermediate, and late planting dates in the results. Planting date treatments were based on cover crop phenology at the time of termination. Early planting date treatments in the corn phase targeted 40% flowering of hairy vetch for termination of the hairy vetch/triticale cover crop mixture (Mischler et al. 2010b). Early planting date treatments in the soybean phase targeted cereal rye anthesis for termination (Mirsky et al. 2009). Cover crop termination was spaced approximately 7 to 10 d apart, subject to environmental conditions, in subsequent intermediate and late planting date treatments. On average, cereal rye termination occurred 7 to 14 d before hairy vetch/triticale (Table 1).

HR cultivation treatments were imposed in the weed management split-split plots. In no-till corn, treatments included a two-pass HR cultivation at 4 and 5 wk after planting (WAP) in comparison to a no-cultivation control. Corn was planted in 76-cm rows, which facilitates the use of HR cultivation. In no-till soybean, weed management split-split-plot treatments included a two-pass HR cultivation 4 and 5 WAP in soybean planted in 76-cm rows in comparison to uncultivated soybean planted in 38-cm rows at PA and DE or drilled in 19-cm rows at MD. This difference in planting method and spacing in the soybean phase allowed us to test the feasibility of relying solely on the cover crop mulch and soybean crop for weed suppression. Narrower row spacing hastens canopy closure but precludes the use of supplemental HR cultivation. A John Deere 886 high-residue cultivator (Moline, IL) was used at PA and a Sukup model (Sheffield, IA) at DE and MD.

Cover and Cash Crop Management. At each location, hairy vetch ('Groff Early Cover'; Cover Crop Solutions, Holtwood, PA) and triticale (Trical 815; King's Agriseeds, Ronks, PA) were drill seeded at 34 kg ha^{-1} per species in 19-cm rows following winter wheat harvest, moldboard plowing, disking,

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Table 1. Aboveground biomass (Mg ha^{-1}) of hairy vetch/triticale and cereal rye cover crops at time of termination with roller-crimper prior to planting no-till corn and soybean, respectively, in each planting date treatment (early, intermediate, late).[a]

	Hairy vetch/triticale mean biomass				Cereal rye mean biomass		
Site-year (termination date)	Early	Intermediate	Late	Site-year (termination date)	Early	Intermediate	Late
		Mg ha^{-1}				Mg ha^{-1}	
Delaware				Delaware			
2011 (May 9–May 31)	3.9 c	5.6 b	7.6 a	2011 (May 2–May 23)	6.7 c	8.0 b	8.8 a
2012 (May 3–May 16)	5.6 b	6.3 ab	6.9 a	2012 (April 25–May 7)	9.0 b	9.0 b	10.8 a
2013 (May 29–June 17)	6.8 a	7.1 a	6.9 a	2013 (May 15–May 28)	7.4 c	8.6 b	10.1 a
Maryland				Maryland			
2011 (May 13–June 3)	4.5 c	6.0 b	6.8 a	2011 (May 3–May 25)	5.1 b	7.4 a	7.6 a
2012 (May 17–May 31)	6.2 a	5.6 a	6.1 a	2012 (April 26–May 17)	5.6 ab	5.0 b	5.8 a
2013 (June 4–June 18)	6.1 a	5.7 a	5.0 b	2013 (May 21–June 5)	8.5 c	9.7 b	11.2 a
Pennsylvania				Pennsylvania			
2011 (June 1–June 16)	6.4 a	6.5 a	6.4 a	2011 (May 26–June 14)	6.5 b	6.7 b	8.5 a
2012 (May 31–June 15)	5.5 b	6.5 a	6.2 a	2012 (May 11–June 1)	4.8 b	4.8 b	5.9 a
2013 (June 1–June 18)	5.7 b	6.2 a	6.4 a	2013 (May 20–June 4)	4.5 c	5.7 b	6.3 a

[a] Data are means averaged across cultivation treatments and replicates ($n = 8$). Similar letters following means within a row indicate no significant difference between planting dates at $P < 0.05$ within a site and year (Keene et al. 2017).

and field cultivation. Cereal rye ('Aroostook'; King's Agriseeds, Ronks, PA) was seeded using a combination of broadcasting at 63 kg ha^{-1} followed by drilling at 126 kg ha^{-1} in 19-cm rows following corn harvest, moldboard plowing, disking, and field cultivation. The combination of broadcast and drill-seeding establishment methods has been shown to increase cereal rye ground cover (J Moyer, personal communication). The following spring, hairy vetch/triticale and cereal rye cover crops were rolled perpendicular to the planting direction with a 3.04-m-wide roller-crimper front mounted to the tractor (Kornecki et al. 2006). In 2011, cover crops were rolled once, but two roller-crimper passes were used in 2012 and 2013 in an effort to improve cover crop termination efficacy. In the final 2 yr, hairy vetch/triticale was rolled just before corn planting and again approximately 7 d later, whereas cereal rye was rolled approximately 7 d before soybean planting and again on the day of planting. Soybean planting ranged from just prior (1 to 2 d) to 14 d before corn planting within planting date treatments. Corn was no-till planted at a rate of 74,000 seeds ha^{-1} at DE and 84,000 seeds ha^{-1} at MD and PA. Soybean was no-till planted at 556,000 seeds ha^{-1} across study locations and treatments (Ryan et al. 2011); organic growers typically use higher soybean seeding rates compared with conventional production to hasten canopy closure and to buffer against crop population loss due to cultivation. Each location used locally adapted corn and soybean varieties appropriate for their region (Keene 2015). Shorter-season corn and soybean varieties were used, as cover crop termination was delayed in alternative planting date treatments (Wallace et al. 2017). At the PA location, early-, intermediate-, and late-planted corn treatments used 99-, 95-, and 85-d hybrids, respectively, compared with 104-, 99-, and 88-d hybrids at DE and MD. For soybean treatments, the PA location used 2.9, 2.7, and 1.1 maturity groups for early, intermediate, and late planting dates, respectively, compared with 4.3, 3.4, and 2.7 maturity groups at DE and MD.

Fertility management differed across experimental sites due to regional differences in availability of animal manures (Keene et al. 2017). At the PA location, liquid dairy manure was broadcast and incorporated with inversion tillage prior to planting hairy vetch/triticale and winter wheat. At the MD location, poultry litter was broadcast and incorporated with inversion tillage before wheat, and pelletized poultry manure was side-dressed in corn using custom subsurface banding equipment. At the DE location, wheat and cereal rye were top-dressed with pelletized poultry manure at early spring green-up, and pelletized poultry manure was broadcast at corn planting.

Weed Seedbank Microplot Establishment. Microplots of identical weed species and densities were established in year 1 of the rotation at each location to assess the efficacy of weed management tactics across sites. Weed microplots were 5 m^2 in size and were sown with 1,500 seeds m^{-2} of common ragweed, giant foxtail, and smooth pigweed. Myers et al. (2004) identified common ragweed, giant foxtail, and smooth pigweed as early-, intermediate-, and late-emerging species, respectively, in

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summer annual crops of the northeastern United States. These groupings reflect peak emergence windows occurring several weeks before typical summer cash crop planting (early emerging), just before or coinciding with planting (intermediate emerging), and after planting (late emerging). Seed lots for each species were collected from local populations at each location in 2009 and 2010 and were broadcast by hand within microplots in late fall of 2010. Cover crops and winter wheat had been planted 1 or 2 mo prior to sowing of microplots. Two microplots were established per split-split plot.

Data Collection. In each cash crop, peak weed biomass and density were measured by species within microplots via destructive sampling in each year of the experiment. Weeds were clipped at the ground surface in a randomly placed 0.5-m^2 quadrat within a representative area of the microplot, sorted to species, oven-dried at 50 C, and weighed. Prior to weed biomass harvest, the density of targeted species (common ragweed, giant foxtail, smooth pigweed) was quantified within the quadrat. To further assess treatment effects on weed abundance, we sampled the resident weed community outside the microplot by harvesting aboveground weed biomass in two randomly placed 0.5-m^2 quadrats at the split-split-plot level (hereafter referred to as the resident weed community). Samples of the resident weed community were sorted to species, dried, and weighed. Weed density and biomass were collected in the wheat phase in early July just prior to harvest. Wheat plots were plowed after harvest, usually in late July, in preparation for hairy vetch/triticale planting. In corn and soybean plots, weed density and biomass were collected in early to mid-August. Subsamples in each split-split plot ($n = 2$) were averaged before analysis for both microplot and resident weed biomass data sets.

Statistical Analysis. All statistical analyses were conducted in R.3.2.4 (R Development Core Team 2016).

Total weed abundance (kg ha^{-1}) in microplots and resident weed community plots was assessed individually and by cash crop (corn, soybean, wheat) with linear mixed-effects models using the 'nlme' package (Pinheiro et al. 2015). Study location, planting date, supplemental weed control, and their interactions were included as fixed effects. Year and block nested within year were fit as random effects. Total weed biomass data were normalized using a $\log_{10}$ transformation after adding a constant (1.0). Mean separations were conducted using Tukey's contrasts (*glht*) in the package 'multcomp' (Hothorn et al. 2008). Analysis of total weed biomass in the winter wheat phase was included to evaluate potential legacy effects of treatments imposed in no-till corn and soybean phases of the rotation. Consequently, we excluded the W–C–S entry point (2011) and used only 2012 to 2013 for analysis of treatment effects in the winter wheat phase.

Population densities (plant m^{-2}) of targeted weed species (common ragweed, giant foxtail, smooth pigweed) were assessed individually and by study location for corn, soybean, and winter wheat phases of the rotation with generalized linear mixed-effects models using a negative binomial distribution and a log link function (*glmer.nb*) in the 'lme4' package (Bates et al. 2016). Models were fit with planting date, supplemental weed control, and their interaction as fixed effects and a year/block nested random effects structure (2011 to 2013 for corn and soybean; 2012 to 2013 for wheat, see above). Each model was checked for overdispersion, and residuals were checked for homoscedasticity and normality. Significance of fixed effects was evaluated using log-likelihood ratio tests (Wald χ^2) to compare full versus reduced models using the *anova* function. We used Tukey's contrasts (*glht*) to compare treatment levels of significant fixed effects.

Given that crop legacy (cash crop by year) effects were confounded with planting date and supplemental weed control treatment effects, we did not specify crop legacy effects in models of weed biomass and density. However, we graphically examined the trajectories of weed biomass and density of targeted weed species in microplots across the 3-yr rotation (C–S–W), averaging across crop entry point. Due to poor cash crop establishment following drought conditions in 2011, the DE location mowed plots prior to weed seed set in early August. As a result, targeted species were either absent in microplots or occurred at densities considerably lower compared with other locations in subsequent growing seasons. Consequently, we excluded the DE location from analysis of targeted weed species density and weed community analyses.

We evaluated the effects of summer annual cash crop (corn, soybean), planting date, supplemental weed control, and their interactions on weed community composition within microplots and resident community plots using permutation-based (nonparametric) multivariate analysis of variance (perMANOVA) in the 'vegan' package (Oksanen 2011). Year was included in the model as a random

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(strata) factor. Prior to analysis, we expressed biomass of each species as a proportion of total biomass per plot to focus the analysis on differences in weed community composition rather than overall weed abundance differences among treatments. Bray-Curtis dissimilarity coefficients were calculated from relative abundance values to characterize differences between weed communities among treatment factors. Statistical evaluations of treatment effects were made using a Monte Carlo procedure (5,000 permutations) at the $P < 0.05$ level. Our primary objective for multivariate analysis of weed microplots was to evaluate treatment effects on changes in composition among the targeted weed species (common ragweed, giant foxtail, smooth pigweed). Consequently, we constrained our analysis to include these three species, two other frequently occurring species (common lambsquarters, *Chenopodium album* L.; yellow nutsedge, *Cyperus esculentus* L.), and a composite of other species. Our primary objective for analysis of the resident weed community was to identify community-level responses to the abiotic and biotic management filters (Booth and Swanton 2002) imposed in the CCORNT system. Consequently, we included all weed species that occurred in more than 2% of sampled quadrats, including volunteer cover crops.

We also used indicator-species analysis on the resident weed community data to determine the strength of associations between individual weed species and treatment factors that significantly ($P < 0.05$) influenced weed community composition, using our perMANOVA results to constrain grouping factors for each study location, in the 'indicspecies' package (De Caceres and Jansen 2016). Indicator values (IVs) were calculated for each species by multiplying the relative abundance and relative frequency within each treatment and range from 0 (no detection) to 100 (exclusive association with treatment). Calculated IVs were tested for significance with a Monte Carlo procedure (1,000 permutations) at the $P < 0.1$ level. To better understand treatment effects on weed community composition, we constructed rank-abundance plots of the 10 most abundant species on a relative scale for each treatment factor that significantly influenced weed community composition, based on perMANOVA results.

Results and Discussion

Cover Crop Performance. Cover crop biomass varied across study location and year in no-till corn and soybean phases (Table 1; Keene et al. 2017). Across years, hairy vetch/triticale biomass ranged from 3.9 to 6.9 Mg ha^{-1} at DE, 4.5 to 6.8 Mg ha^{-1} at MD, and 5.5 to 6.4 Mg ha^{-1} at PA. Delaying termination of hairy vetch/triticale over approximately a 14- to 21-d period did not consistently increase aboveground biomass in each year. However, in the intermediate planting date treatment at each location and across years, cover crop biomass exceeded 5 Mg ha^{-1}, which is considered a minimum threshold for consistent weed suppression of summer annual weeds in the northern mid-Atlantic (Mohler and Teasdale 1993). Cereal rye biomass ranged from 6.7 to 10.8 Mg ha^{-1} at DE, 5.0 to 11.2 Mg ha^{-1} at MD, and 4.5 to 8.5 Mg ha^{-1} at PA across the years of the study. Delaying termination (14 to 21 d) resulted in increases in cereal biomass in most cases at each study location. The phenological traits of cereal rye and hairy vetch likely contribute to observed differences in biomass response to delayed termination between cover crop species. Studies suggest that hairy vetch biomass peaks at midbloom (Hoffman et al. 1993), which coincides with the termination timing in our early to intermediate planting date treatments.

Cover crop biomass levels observed in this study are consistent with recent mid-Atlantic studies that have documented regional differences in cereal rye (Mirsky et al. 2017b) and hairy vetch (Mirsky et al. 2017a) biomass potential. Previous studies have also demonstrated regional differences in the interaction between cover crop biomass production and weed suppression in the mid-Atlantic. Acceptable levels of weed suppression from hairy vetch/winter cereal mixtures or cereal rye can be achieved with 5 Mg ha^{-1} of aboveground dry-matter biomass in more northern latitudes (PA, NY) of the mid-Atlantic (Liebert et al. 2017; Mischler et al. 2010a; Nord et al. 2011), whereas 8,000 to 10,000 Mg ha^{-1} is likely needed at more southern latitudes (Smith et al. 2011b; Teasdale and Mohler 2000).

Total Weed Abundance. Total microplot weed biomass (kg ha^{-1}) was influenced by study location ($F_{(2,187)} = 36.7$, $P < 0.001$) and supplemental weed control ($F_{(1,187)} = 28.9$, $P < 0.001$) in no-till corn (Figure 1). Across planting dates and supplemental weed control treatments, weed biomass was higher at the MD location (>1,000 kg ha^{-1}) compared with the DE and PA locations (<1,000 kg ha^{-1}). HR cultivation decreased total weed biomass across planting dates and study locations, resulting in an average 58%, 23%, and 62% decrease in weed

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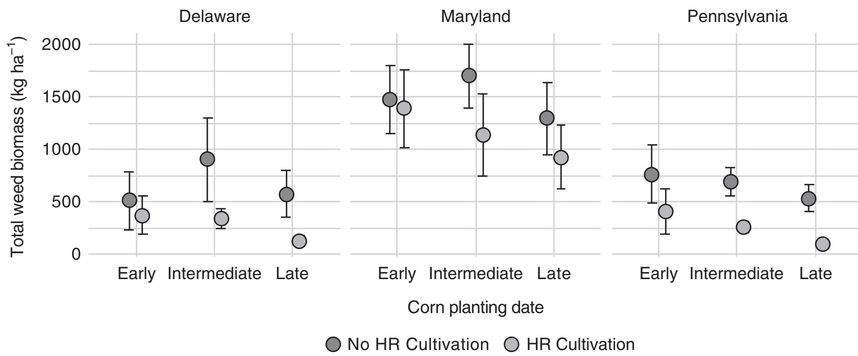

Figure 1. Total microplot weed biomass (kg ha^{-1}) collected in late August in corn phase of rotation. Data presented by planting date and supplemental weed control treatment (No HR Cultivation, control; HR Cultivation, high-residue cultivation) at each study location. Data are microplot means averaged across the 2011–2013 growing seasons ± SE. Significant treatment effects include study location ($F_{(2,187)} = 36.7$; $P < 0.0001$) and supplemental weed control ($F_{(1,187)} = 28.9$; $P < 0.0001$); statistical inferences based on $\log_{10}$-transformed data.

biomass relative to the uncultivated controls at DE, MD, and PA, respectively. Similar study location ($F_{(2,187)} = 15.2$, $P < 0.001$) and supplemental weed control ($F_{(1,187)} = 9.6$, $P < 0.01$) effects were observed in analysis of resident weed community biomass, which was comparatively lower than microplots, ranging from 250 kg ha^{-1} at PA to 750 kg ha^{-1} at MD. HR cultivation resulted in an average 38%, 33%, and 78% decrease in total biomass of the resident weed community at DE, MD, and PA, respectively, compared with the no-cultivation control.

We observed similar main effects of treatments in no-till soybean (Figure 2). Total microplot weed biomass (kg ha^{-1}) was influenced by study location ($F_{(2,187)} = 40.4$, $P < 0.001$) and supplemental weed control ($F_{(1,187)} = 28.1$, $P < 0.001$). With exception of the PA location, total weed biomass was higher in soybean compared with the corn phase of the rotation, ranging from >1,000 kg ha^{-1} at DE and MD to <500 kg ha^{-1} at PA. The use of HR cultivation decreased total weed biomass across planting dates and study locations, resulting in an average 20%, 41%, and 78% decrease in biomass relative to the control at DE, MD, and PA, respectively. In analysis of resident weed community biomass (kg ha^{-1}), we observed significant study location ($F_{(2,187)} = 61.1$, $P < 0.001$) and supplemental weed control ($F_{(1,187)} = 7.3$, $P < 0.01$) effects. Resident weed community biomass ranged from approximately 1,000 kg ha^{-1} at DE and MD to 100 kg ha^{-1} at PA. The average decrease in biomass attributable to HR cultivation was lower, but produced similar trends, in comparison to microplots.

Total weed biomass collected just prior to harvest in winter wheat remained low across locations in 2012 and 2013, with more than 80% of samples below 100 kg ha^{-1} (Figure 3). It is important to note that weed biomass data collection targeted peak biomass conditions in each cash crop, which

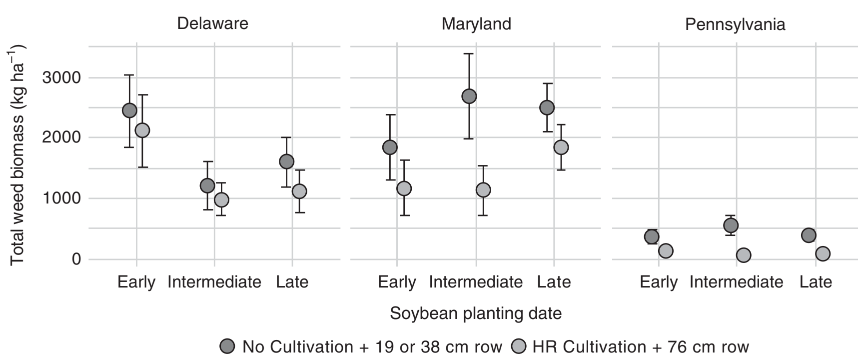

Figure 2. Total microplot weed biomass (kg ha^{-1}) collected in late August in soybean phase. Data presented by planting date and supplemental weed control treatment (no high-residue cultivation + 19- or 38-cm row; high-residue cultivation + 76-cm row) at each study location. Data are microplot means averaged across the 2011–2013 growing seasons ± SE. Significant treatment effects include study location ($F_{(2,187)} = 40.4$; $P < 0.0001$) and supplemental weed control ($F_{(1,187)} = 28.1$; $P < 0.0001$); statistical inferences based on $\log_{10}$-transformed data.

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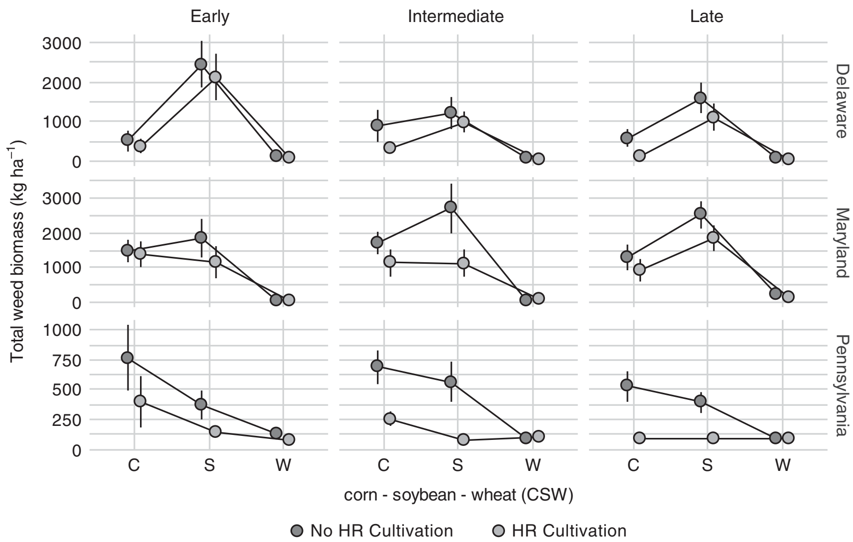

Figure 3. Total microplot weed biomass (kg ha^{-1}) across corn–soybean–winter wheat (CSW) rotation by planting date (early, intermediate, late) and supplemental weed control treatments at each study location. Treatments were imposed in no-till corn and soybean phases of the rotation only. High-residue (HR) cultivation was conducted approximately 4 and 5 wk after planting. No-HR cultivation treatments included a cultivation control in no-till corn and soybean planted in 19- or 38-cm rows, depending on location, without HR cultivation. Data are weed microplot means averaged across replicates and entry points ± SE ($n = 12$).

occurred approximately a month earlier in wheat (early July) compared with corn and soybean (early August). Based on our observations, summer annual weeds that emerged in the wheat did not set seed before tillage of the wheat residue in mid-August. These results underscore the importance of integrating cool-season crops into warm-season crop rotations as an integrated weed management tactic (Liebman et al. 2001). In a CCORNT system, integration of winter grain or perennial forage will likely be an important weed management tactic for truncating potentially rapid weed seedbank population increases following no-till corn and soybean phases. Integration of cool-season annuals or perennial forage crops may be particularly important following years when weed suppression is suboptimal in summer annual cash crops, as has been documented in other studies (Anderson 2005, 2010).

The effect of HR cultivation on total weed biomass compared with control treatments was highly variable (20% to 78% reduction in biomass) in our study, because in-row weed abundance was highly variable and not controlled by HR cultivation. In CCORNT systems, in-row weed abundance is influenced by the level of soil and surface mulch disturbance associated with no-till planting in high-residue surface mulches. Soil disturbance can either promote recruitment of late-emerging summer annual weeds by breaking dormancy (Mirsky et al. 2013; Teasdale and Mirsky 2015) or control early-emerging weed species by uprooting or burying weed seedlings (Liebert et al. 2017). Higher disturbance to the cover crop mulch, due to use of aggressive row cleaners to ensure adequate seed placement, can promote germination and recruitment of in-row weeds following planting (Mirsky et al. 2012; Wallace et al. 2017).

Irrespective of in-row weed competition, our study demonstrates that HR cultivation consistently reduces total weed biomass, and thus weed–crop competition and potential fecundity. In CCORNT systems, HR cultivation may be best employed as an adaptive management practice. For example, Nord et al. (2011) demonstrated that HR cultivation was most effective at locations with high weed seedbanks or below-optimum cereal rye biomass production in a rolled no-till soybean system, but was likely not necessary under low weed pressure or when high levels of cereal rye biomass were achieved. Under high weed seedbank conditions, we suggest that two HR cultivation passes at 4 and 5 (or 6) WAP are needed to improve weed control efficacy; a second pass helps dislodge weeds that may survive the first pass and increases control of weed species with later emergence periods that may germinate after the first cultivation pass (Keene et al. 2016; Zinati et al. 2017). We have observed that some weed species are more likely to persist in cover crop mulches. Specifically, large-seeded summer annual weeds, such as velvetleaf (*Abutilon theophrasti* Medik) and perennial weeds such as yellow nutsedge and Canada thistle [*Cirsium arvense* (L.) Scop.] are likely to increase in reduced-tillage systems because they emerge through high rates of cover crop mulches (Mischler et al. 2010a; Mohler and Teasdale 1993).

Species-Level Responses to Management Tactics. The effect of planting date and supplemental weed control on weed densities differed among targeted weed species, cash crops, and study locations (Table 2). Interactions between planting date and supplemental weed control were only observed in analysis of common ragweed populations; therefore, main effects of planting date and supplemental weed control are presented, and interactions are noted when significant.

Common ragweed density was lower (<10 plant m^{-2}) compared with giant foxtail and smooth pigweed across planting dates in both no-till corn and soybean. However, common ragweed density was higher ($P < 0.001$) in early-planted corn compared with late-planted corn at the MD and PA locations (Figure 4). Across soybean planting dates at the PA location, HR cultivation (76-cm rows) lowered ($P < 0.01$) common ragweed density in comparison with noncultivated soybean planted on 38-cm rows (Figure 5). In comparison, HR cultivation lowered common ragweed density in late-planted corn and soybean at the MD location, but did not affect densities at early and intermediate planting dates. High common ragweed densities were observed in the winter wheat phase, averaging 16 and 37 plants m^{-2} at MD and PA, respectively,

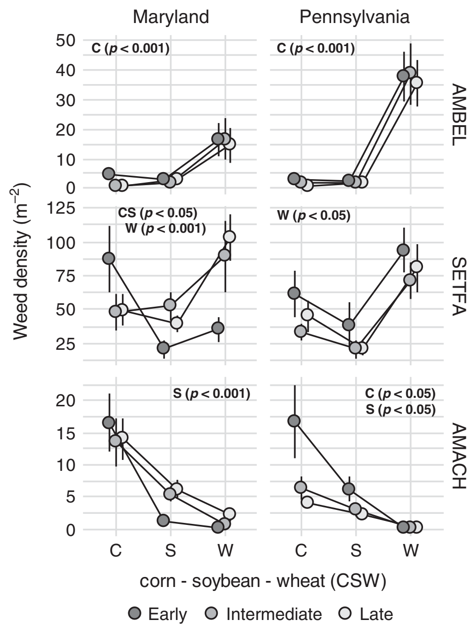

Figure 4. Common ragweed (AMBEL), giant foxtail (SETFA), and smooth pigweed (AMACH) density (plant m^{-2}) in corn–soybean–wheat (CSW) rotation by planting date (early, intermediate, late) at the Maryland and Pennsylvania locations. Data are weed microplot means averaged across replicates, supplemental weed control treatments, and entry points ± SE (corn and soybean, $n = 24$). Significant planting date main effects ($P < 0.05$) are denoted by crop (CSW); statistical inferences based on a negative binomial distribution.

across treatments and growing seasons. In comparison to the other target species, common ragweed is more likely to emerge and establish in late spring prior to winter wheat canopy closure. At the PA

Table 2. Effects of planting date, supplemental weed control, and their interaction (PD × SWC) on weed species density in corn, soybean, and winter wheat phases of rotation at Pennsylvania and Maryland locations.

	Corn phase[b]			Soybean phase[c]			Winter wheat phase[d]		
Fixed effects[a]	AMBEL[e]	SETFA	AMACH	AMBEL	SETFA	AMACH	AMBEL	SETFA	AMACH
	Wald χ^2								
Maryland									
Planting date	25.2***	6.5*	NS	NS	12.6**	16.7***	NS	14.8***	NS
Suppl weed ctl	NS	NS	10.9***	NS	5.7*	11.8***	NS	NS	NS
PD × SWC	8.1*	NS	NS	7.8*	NS	NS	NS	NS	NS
Pennsylvania									
Planting date	13.0***	NS	8.7*	NS	NS	6.9*	NS	8.0*	NS
Suppl weed ctl	NS	22.1***	NS	7.5**	11.4***	NS	NS	5.9*	NS
PD × SWC	NS	NS	NS	NS	NS	NS	6.0*	NS	NS

[a] Evaluation of fixed effects are based on likelihood ratio tests (Wald χ^2) using random effects as null model. Significance ($Pr > \chi^2$) of model terms shown as: NS, $P > 0.05$; *, $P < 0.05$; **, $P < 0.01$; ***, $P < 0.001$.
[b] Supplemental weed control in corn phase includes high-residue cultivation and control.
[c] Supplemental weed control in soybean phase includes high-residue cultivation on 76-cm rows and no cultivation on 38-cm rows.
[d] Fixed effects imposed only in corn and soybean phase. ANOVA of wheat phase measures legacy effects of treatments in 2012–2013 only.
[e] Abbreviations/Bayer codes: AMACH, smooth pigweed; AMBEL, common ragweed; PD, planting date; SETFA, giant foxtail; SWC, soybean–wheat–corn; NS, not significant.

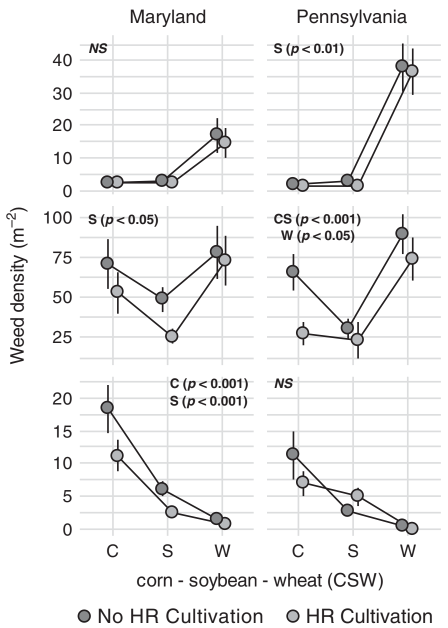

Figure 5. Common ragweed (AMBEL), giant foxtail (SETFA), and smooth pigweed (AMACH) density (plants m^{-2}) in corn–soybean–wheat rotation by supplemental weed control treatment (No HR cultivation, HR cultivation) at the Maryland and Pennsylvania locations. High-residue (HR) cultivation was conducted approximately 4 and 5 wk after planting. No HR cultivation treatments included a cultivation control in no-till corn and soybean planted in 19- or 38-cm rows, depending on location, without HR cultivation. Data are weed microplot means averaged across replicates, planting date treatments, and entry points ± SE ($n = 36$). Significant supplemental weed control main effects ($P < 0.05$) are denoted by crop (CSW); statistical inferences based on a negative binomial distribution.

location, an interaction between planting date and supplemental weed control was detected (Table 2), where treatment legacies resulted in similar common ragweed densities across planting date treatments within cultivated plots. However, within plots that did not use HR cultivation, common ragweed densities were higher in early-planted treatments compared with other planting dates. This result is consistent with previous studies that have demonstrated the utility of HR cultivation for control of early-emerging summer annual species such as common ragweed (Liebert et al. 2017; Nord et al. 2011).

Giant foxtail densities ranged from 20 to 105 plants m^{-2} across treatments and study locations. At the MD location, giant foxtail density responded strongly to planting date (Table 2). Early corn planting dates resulted in higher giant foxtail density in comparison to late-planted corn, and early soybean planting dates resulted in lower giant foxtail densities in comparison to other planting date treatments (Figure 4). Lower giant foxtail density in early-planted soybean likely contributed to lower densities in the following winter wheat phase of the rotation compared with other planting dates. We observed similar effects on giant foxtail density at the PA location, but populations were less responsive to planting date. In both corn and soybean phases of the rotation, giant foxtail density was higher but more variable in early-planted treatments. The legacy of this planting date effect likely contributed to greater observed giant foxtail densities in winter wheat plots that followed early-planted corn and soybean. The use of HR cultivation resulted in lower giant foxtail density within each cash crop at the PA location and in soybean at the MD location (Figure 5).

Smooth pigweed density was below 20 plants m^{-2} across cash crops, treatments, and study locations. Similar rotational trends were observed across locations, where smooth pigweed density was highest in the corn phase and declined in both the soybean and winter wheat phases of the rotation. Early-planted soybean resulted in lower pigweed density compared with other treatments at the MD location (Figure 4). In comparison, early-planted corn and soybean resulted in higher smooth pigweed density compared with other treatments at the PA location. Across planting dates, supplemental weed control decreased pigweed densities in both the corn and soybean phases at MD, but did not affect pigweed densities at the PA location (Figure 5).

Distance-based multivariate analysis indicated that summer annual cash crop phase ($F_{(1,372)} = 35.6$; $P < 0.001$) and planting date ($F_{(2,372)} = 1.8$; $P = 0.02$) significantly affected weed community composition within microplots. On average, targeted weed species (common ragweed, giant foxtail, smooth pigweed) comprised greater than 75% of total weed biomass in microplots within both corn and soybean phases of the rotation. Relative abundance (% of total weed biomass) patterns of these targeted species helps identify species-level responses to management factors, which contribute to overall changes in weed community composition (Table 3). Common ragweed was more dominant in soybean (39%) compared with corn (10%), whereas giant foxtail and smooth pigweed were more dominant in corn, comprising 46% and 22% of total biomass, respectively. Across summer annual cash crops, common ragweed became less abundant as planting dates were delayed, whereas giant foxtail

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Table 3. Relative abundance (% of total weed biomass) of common ragweed (AMBEL), giant foxtail (SETFA), and smooth pigweed (AMACH) by significant treatment factors (crop, planting date) influencing weed community composition (PerMANOVA) in microplots.

Treatment	AMBEL	SETFA	AMACH
Crop	— Relative abundance (±95% confidence intervals) —		
Corn	10 (7, 13)	46 (41, 51)	22 (18, 27)
Soybean	39 (33, 45)	36 (30, 41)	5 (3, 7)
Planting date			
Early	30 (23, 37)	37 (31, 43)	12 (9, 16)
Intermediate	25 (19, 31)	41 (35, 48)	13 (9, 17)
Late	19 (13, 24)	44 (37, 50)	16 (11, 20)

and smooth pigweed increased as a percentage of total biomass as planting dates were delayed.

Weed species density and relative abundance trends in our study are consistent with previous organic, no-till component studies and contribute additional insight into the effects of multitactic control strategies on population trajectories of common weed species in a CCORNT system. Common ragweed has a low base temperature for germination (Forcella et al. 1997) and is one of the earliest emerging summer annuals in the mid-Atlantic (Myers et al. 2004). Secondary dormancy occurs with increasing spring temperatures, which results in a truncated emergence period relative to other summer annual species. Recent studies have suggested that these traits are well adapted to a no-till soybean system, which enables common ragweed to become a dominant species by emerging in the cereal rye cover crop prior to termination and surviving the roller-crimping operation (Nord et al. 2012). Teasdale and Mirsky (2015) suggest that greater canopy closure of hairy vetch and later termination dates create a less suitable niche for common ragweed in no-till corn. Though densities remained low in corn and soybean in our study, higher relative abundance of common ragweed in soybean and at earlier planting dates likely contributed to high common ragweed densities in the winter wheat phase. Our observations suggest that winter wheat harvest and postharvest tillage prevented common ragweed seed production, highlighting the utility of crop rotation and integration of late-summer cover crops that add temporal diversity to tillage operations for managing seedbank trajectories.

In contrast, smooth pigweed was more abundant in no-till corn and at later planting dates. Smooth pigweed densities declined in both the soybean and winter wheat phases of the rotation. Functional traits that likely contribute to these observed trends include a later emergence periodicity in the mid-Atlantic (Myers et al. 2004), induced secondary dormancy via low soil moisture (Forcella et al. 1997), and higher nitrogen acquisition and use efficiency in comparison with other summer annual weeds (Blackshaw et al. 2003).

Giant foxtail was abundant in each cash crop in our 3-yr rotation, which suggests that the CCORNT system may select for this species, leading to it becoming a dominant species over time. Foxtail germination periodicity overlaps with the planting date ranges in both no-till corn and soybean. Foxtail species are also likely to persist in a range of surface mulch residue levels and cover crop species mixtures, because germination is relatively insensitive to changes in light conditions (Dekker 2003). Furthermore, Teasdale and Mirsky (2015) suggest that due to seedling establishment via leaf elongation, monocots may have a competitive advantage during the establishment phase over dicot species that frequently rely on hypocotyl elongation to emerge through surface mulch.

Resident Weed Community Response. Analysis of the resident weed community provided insight into the strength of management-related filters on weed species with functional traits that differed from targeted summer annual weed species. Similar to microplots, cash crop ($F_{(1,226)} = 9.3$; $P < 0.001$) and planting date ($F_{(2,226)} = 3.7$; $P < 0.001$) affected resident weed community composition at the MD location, and a significant interaction between cash crop and planting date ($F_{(1,273)} = 1.5$; $P = 0.05$) was detected at the PA location. We used rank abundance plots, based on relative abundance values, and indicator-species analysis to further identify species-level responses to these management factors that contribute to shifts in weed community composition. At the MD location, smooth pigweed was associated (IV = 62) with the corn phase (Figure 6). In contrast, yellow nutsedge and Pennsylvania smartweed (*Polygonum pensylvanicum* L.) were associated (IV = 66 and 52, respectively) with the soybean phase. Other than yellow nutsedge, resident weed communities were dominated by summer annual grass and broadleaf species at the MD location. Across summer annual cash crops, common lambsquarters and Pennsylvania smartweed were associated (IV = 42 for both species) with earlier planting dates, giant foxtail was associated (IV = 57) with intermediate planting dates, and smooth pigweed was associated (IV = 50) with later planting dates.

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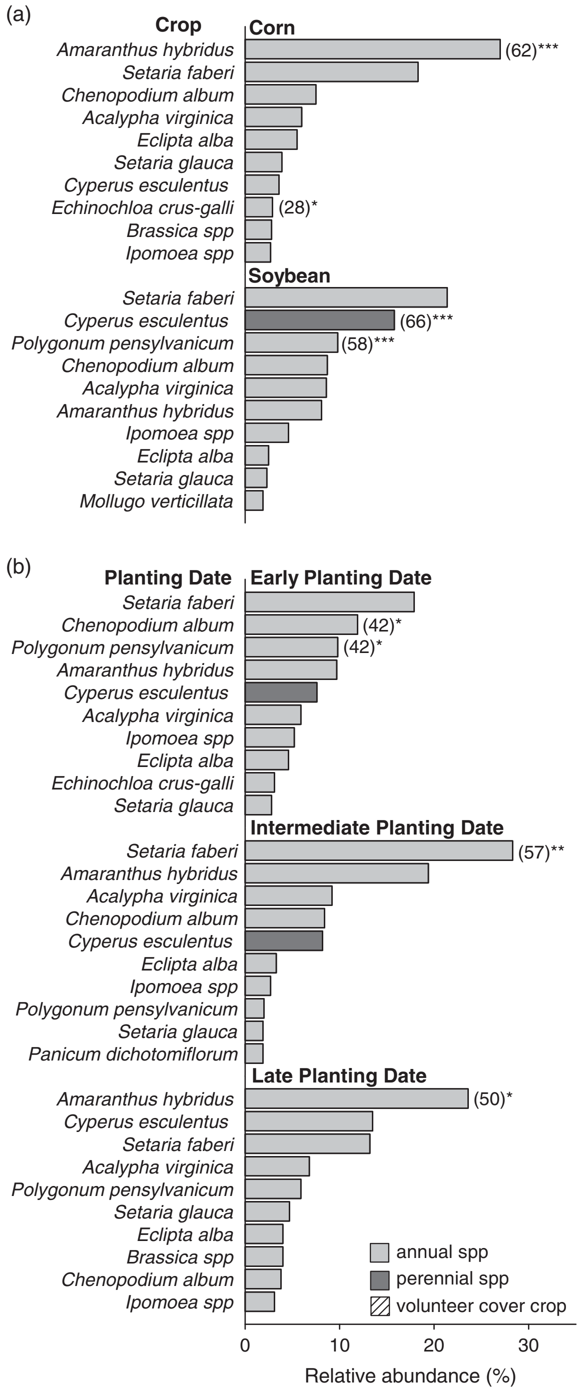

Figure 6. Effect of (a) cash crop (corn, soybean) and (b) planting date (early, intermediate, late) on relative abundance (% of total biomass) of weedy species in the resident weed community at the Maryland location. Rank abundance plots include summer and winter annual species (gray) and perennial species (dark gray). Indicator values (IV) are presented in parentheses for weed species significantly associated (indicator-species analysis) with treatment. Level of significance (Monte Carlo procedure; 1,000 runs) is denoted with asterisks (*, $P < 0.05$; **, $P < 0.01$; ***, $P < 0.001$).

Total weed biomass in resident weed community plots was low (<250 kg ha^{-1}) across the 3-yr rotation at the PA location. However, evaluation of rank abundance plots highlights the significance of cover crop management in CCORNT systems. Incomplete termination with the roller-crimper resulted in hairy vetch becoming a substantial component of the weed flora (% relative abundance) in the corn phase (Figure 7). Incomplete termination of cereal rye with the roller-crimper and volunteer recruitment of hairy vetch following seed production in the preceding corn phase resulted in both species comprising a high proportion of total weed abundance in the soybean phase. In the corn phase of the rotation, yellow nutsedge and common lambsquarters were associated (IV = 31 and 29, respectively) with the early planting date, and smooth pigweed was associated (IV = 43) with the intermediate planting date. In the soybean phase, cereal rye occurred across planting dates but was more strongly associated (IV = 47) with the late planting date.

Increased perennial weed abundance is associated with reduced-tillage systems (Buhler et al. 1994), and some perennial weeds such as Canada thistle have been shown to increase in reduced-tillage organic systems (Smith et al. 2011a). In our study, perennial weeds were a minor component of the weed community, limited to yellow nutsedge and several other infrequently occurring species. Though we would suggest that CCORNT are less susceptible to increased perennial weed abundance, given that primary tillage occurs once per year, future research should seek to understand perennial weed dynamics over a longer time interval in CCORNT systems. More problematic, however, is the potential for volunteer cover crops to become persistent weed species in CCORNT systems. In our study, termination of hairy vetch and cereal rye improved as planting date was delayed across locations, but hairy vetch and cereal rye seed production occurred across planting dates due to incomplete termination with the roller-crimper, resulting in volunteer recruitment of cover crops in subsequent phases of the rotation (Keene et al. 2017). Delayed cover crop termination is both a primary weed management tactic and a primary driver of cover crop termination efficacy. Therefore, the design of integrated weed management programs in CCORNT systems should carefully consider these potential agronomic trade-offs. Looking forward, improved cover crop termination management practices are needed with the roller-crimper to prevent cover crop seed production and the proliferation of volunteer cover crops.

The viability of CCORNT systems hinges on the development of robust multitactic weed management approaches. Our study provides new evidence that weed management in CCORNT systems can be effective if diverse crop and weed management practices are employed. Observed population trajectories of three common summer annual weed species (common ragweed, giant foxtail, smooth pigweed) suggest that inclusion of a winter grain may prevent rapid weed seedbank increases if weed suppression is suboptimal in no-till corn and soybean phases of the rotation. In many areas of the mid-Atlantic, organic grain producers use longer rotations that include perennial forages (Wallace et al. 2017), which can hasten weed seedbank decline in the event that no-till production of summer annual cash crops results in high seedbank inputs (Liebman and Davis 2000; Teasdale et al. 2004). Weed management programs in CCORNT systems will also require supplemental forms of weed control, such as HR cultivation, that can be employed as an adaptive management practice under conditions that promote high weed seedbanks or suboptimal surface mulch. Our research suggests that delaying cover crop termination to produce high levels of biomass, and thus better weed-suppressive mulches, is an inconsistent weed management tactic that also creates agronomic trade-offs that must be negotiated. Our results also support a growing body of evidence that suggests optimizing cover crop management, rather than biomass production, should be the primary management objective (Liebert et al. 2017; Nord et al. 2012; Teasdale and Mirsky 2015). To optimize cover crop management to enhance weed suppression in CCORNT systems, it will be necessary for growers to understand how the timing of crop and weed management operations, functional traits of species in the weed flora, and local climate or production system factors interact to select for particular weed communities. It will also be necessary to evaluate trade-offs related to cash crop performance and other valued ecosystem services. For example, delayed planting may contribute to improved weed management but reduce cash crop yields due to a shortened growing season in the mid-Atlantic region. Additional research is needed to determine whether this multi-tactic approach to weed management will permit long-term productivity and profitability of CCORNT systems.

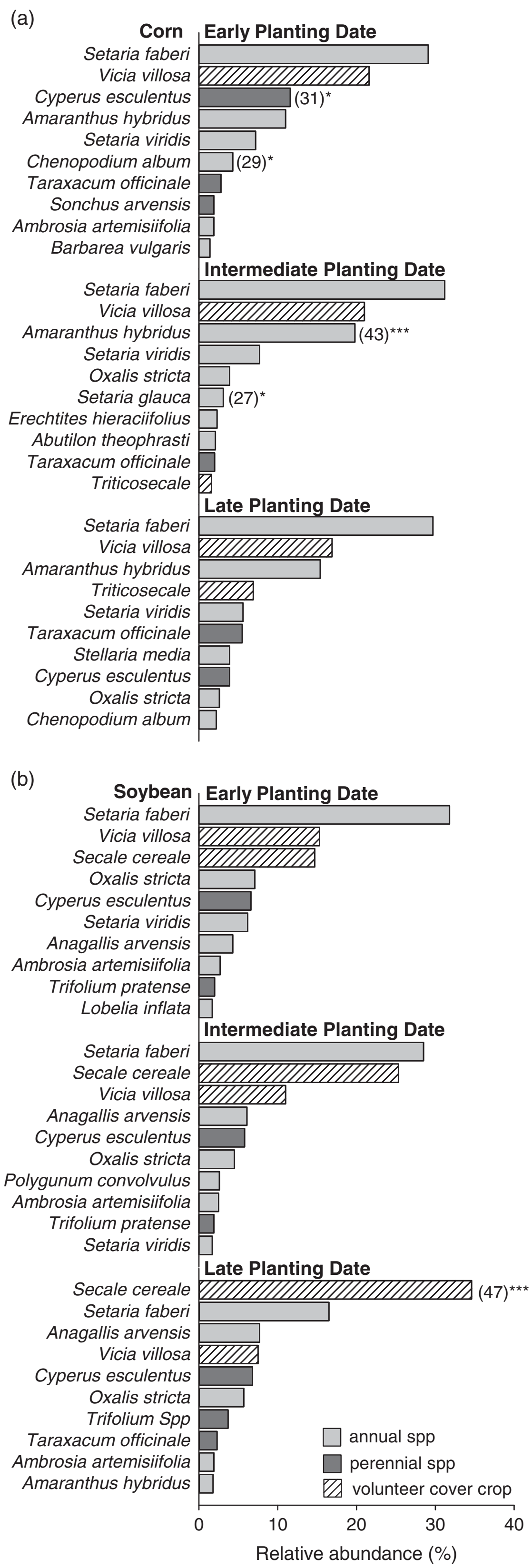

Figure 7. Effect of planting date in (a) corn and (b) soybean phases on relative abundance (% of total biomass) of weedy species in the resident weed community at the Pennsylvania location. Rank abundance plots include summer and winter annual species (gray), perennial species (dark gray) and volunteer cover crops (checked white). Indicator values (IV) are presented in parentheses for weed species significantly associated (indicator-species analysis) with treatment. Level of significance (Monte Carlo procedure; 1,000 runs) is denoted with asterisks (*, $P < 0.05$; **, $P < 0.01$; ***, $P < 0.001$).

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