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Management of Overwintering Cover Crops Influences Floral Resources and Visitation by Native Bees

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ABSTRACT The incorporation of cover crops into annual crop rotations is one practice that is used in the Mid-Atlantic United States to manage soil fertility, suppress weeds, and control erosion. Additionally, flowering cover crops have the potential to support beneficial insect communities, such as native bees. Because of the current declines in managed honey bee colonies, the conservation of native bee communities is critical to maintaining "free" pollination services. However, native bees are negatively affected by agricultural intensification and are also in decline across North America. We conducted two experiments to assess the potential of flowering cover crops to act as a conservation resource for native bees. We evaluated the effects of cover crop diversity and fall planting date on floral resource availability and visitation by native bees for overwintering flowering cover crop species commonly used in the Mid-Atlantic region. Cover crop species, crop rotation schedule, and plant diversity significantly influenced floral resource availability. Different cover crop species not only had different blooming phenologies and winter survival responses to planting date, but attracted unique bee communities. Flower density was the primary factor influencing frequency of bee visitation across cover crop diversity and fall planting date treatments. The results from these experiments will be useful for informing recommendations on the applied use of flowering cover crops for pollinator conservation purposes.

KEY WORDS flowering cover crop, native bee, conservation, agriculture

Pollination as an ecosystem service is vital to the reproduction of many of the world's food crops and other flowering plants, and it is estimated that animal-mediated pollination (primarily by bees) is required for 35% of the world's total food production and 87.5% of all flowering plants (Klein et al. 2007, Ollerton et al. 2011). While managed honey bee colonies are most often used for agricultural pollination, native bees are also known to play an important role in crop pollination (Kremen et al. 2002; Ricketts 2004; Morandin and Winston 2005; Greenleaf and Kremen 2006a,b). Although pollination services are often essential for agricultural production, the importance of native bee communities extends far beyond this purpose.

The world's pollinators are in decline. In addition to the recent, well-documented decrease in managed honey bee colonies (VanEngelsdorp et al. 2009, Williams et al. 2010), there is evidence for a global decline in other pollinator groups as well as many pollinator-dependent plants (National Research Council 2007, Potts et al. 2010). Some possible causes of this decline include loss of natural habitat, agricultural pesticides, disease, and climate change (Potts et al. 2010). However, it is most likely that the interaction of multiple factors has contributed to the widespread decline in pollinators globally. Habitat loss and fragmentation, in particular, are often listed among the greatest and most common threats to wild pollinators, particularly bees (Kremen et al. 2002, Ricketts 2004, Goulson et al. 2008, Winfree et al. 2009).

Conversion of native habitat to agricultural production is often associated with a decrease in biodiversity and increased land simplification (Matson et al. 1997, Tilman et al. 2001). Indeed, bees are the insect group shown to be the most negatively affected by agricultural intensification (Hendrickx et al. 2007). Because total land-use change has been predicted to have the greatest effect on global biodiversity of terrestrial ecosystems over the next 100 yr (Sala et al. 2000), determining alternative scenarios that limit the effects of habitat change on native pollinators is a significant consideration for pollinator conservation.

One strategy for increasing conservation of biodiversity and function in agricultural systems is a trend toward organic or diversified farming. Compared with conventional farming, organic agriculture can increase biodiversity and ecosystem services (Hole et al. 2005, Kremen and Miles 2012) and support a greater diversity of native bees (Holzschuh et al. 2006). Additionally, temporal variations in resource availability or location can significantly affect arthropod populations (Vasseur et al. 2013). By focusing on an array of practices including preservation of habitat refuges, wildlife-friendly farming, and the seasonal resource variations across the landscape, an optimal conservation strategy may be developed for a wide range of farm types or locations (Hodgson et al. 2010). As a partial solution to this

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conservation need, we considered the incorporation of overwintering cover crops into organic farming systems to enhance floral resources both spatially and temporally across the agricultural landscape.

Cover crops are species grown within fallow periods in an annual crop rotation schedule. In temperate cropping systems, the most commonly used species are grasses and legumes. Cover crops can be planted at almost any time during the year depending on the crop rotation, local climate, and goals of the producer. Most farmers plant cover crops for within-field erosion control, soil fertility management, or weed suppression (Lal et al. 1991, Snapp et al. 2005, Clark 2007, Schipanski et al. 2014). However, because the inclusion of cover crops into an annual crop rotation potentially increases spatial and temporal plant diversity levels, it can also act as a conservation tactic. By selecting cover crops that also produce flowers attractive to native pollinators, this practice can benefit crop productivity as well as supplement resources to native wildlife populations and their associated services.

The addition of supplemental floral resources to an agricultural landscape is beneficial to native bee communities and is often used to conserve pollinators (Tuell et al. 2008, Winfree 2010). The research presented here focuses on whether the addition of overwintering, spring-blooming cover crop species could achieve the same purpose. This timeframe is especially important because some native bee species benefit from an increase in springtime floral resources (Elliott 2009, Williams et al. 2012). Agricultural landscapes dominated by annual crops often lack these early-season flowers compared with natural or fallow areas (Winfree et al. 2007, Mandelik et al. 2012, Williams et al. 2012). Accordingly, increasing spring flowering resources within cultivated fields could have a large influence on overall resource availability for native bees during this time of the year.

Incorporating flowering cover crops into a rotation schedule is an agricultural conservation strategy with the opportunity to meet the needs of both the grower and the native pollinator community. However, to develop appropriate recommendations to farmers and other land managers interested in achieving these dual benefits, it is important to select cover crops appropriate for a particular production system. Some of the factors that need to be considered in the selection of cover crops include bloom period and phenology, effects of fall planting and spring termination dates, and the bee community associated with particular cover crop species. For example, one grower may be interested in a cover crop species that benefits the greatest diversity of pollinators, while another may want to focus on those bees that are needed to pollinate a particular cash crop. Additionally, as cover crops are grown for a multitude of agronomic benefits, many farmers have demonstrated recent interest in planting diverse cover crop mixtures in an effort to maximize the ecosystem services from different plant groups (Creamer et al. 1997, Groff 2008). By planting cover crop polycultures, famers may expand the overall ecosystem service benefits provided by cover cropping. However, if a goal of using cover crop mixtures is intended to provide pollinator conservation benefits, it is important to have an understanding of the effect of increased cover crop plant diversity on the potential visiting pollinator community.

Here we present the results of two experiments to determine the influence of agricultural management on three overwintering cover crop species. We monitored pollinator conservation potential as determined by available floral resources and associated native bee communities. The goal of Experiment 1 was to investigate the effect of increased cover crop diversity on available floral resources within the defined timeframe of a typical organic field crop rotation. Experiment 2 focused on the impact of fall planting date timing on cover crop bloom onset, duration, and intensity outside the restrictions of a defined cash crop rotation.

Materials and Methods

Site and Plot Establishment. *Experiment 1.* This experiment was conducted at a single site established on ~11 ha of land at the Pennsylvania State University Russell E. Larson Research and Education Center (RELREC) near Rock Springs, Pennsylvania. The dominant soil type at the site is Hagerstown silt loam with soil texture being predominantly clay loam with variability in silt, clay, and sand. This land is in transition to organic certification and was managed in accordance with the USDA National Organic Standards (U.S. Department of Agriculture [USDA] 2013). No pest control materials have been applied at the site since the initiation of the transition in 2012.

To study the benefits and trade-offs of cover crop diversity on a suite of ecosystem functions, a full-entry, stripped, randomized complete block design field experiment was established at RELREC. This experiment is part of a larger project to determine the multiple benefits and trade-offs of cover crop species grown in monoculture and in mixtures on several ecosystem services, including soil nutrient management, weed suppression, and insect pest regulation. The 12 treatments in the larger experiment are composed of six fall-planted cover crop species grown in monoculture, five cover crop mixture treatments, and a fallow treatment embedded in a winter wheat (*Triticum aestivum* L.), corn (*Zea mays* L.), and soybean (*Glycine max* (L.) Merr.) rotation. Treatments were each replicated four times.

In Experiment 1, we focused on three treatments within the larger experiment: canola (*Brassica napus* L.'*Wichita*') planted in monoculture (12.7 kg/ha); a four species mix including canola (6.3 kg/ha), medium red clover (*Trifolium pratense* L.; 6.7 kg/ha), Austrian winter pea (*Pisum sativum* subsp. *arvense* L.; 43.4 kg/ha), and cereal rye (*Secale cereale* L.; 27.8 kg/ha); and a six species mix that included canola (3.1 kg/ha), medium red clover (3.4 kg/ha), Austrian winter pea (21.7 kg/ha), cereal rye (27.8 kg/ha), forage radish (*Raphanus sativus* L.; 3.6 kg/ha) and oats (*Avena sativa* L.; 25.8 kg/ha). Cover crop treatment plots were planted on 25–26 August 2012 after the harvest of a preceding barley crop. Each plot measured ~24 m by 27 m. All cover crop seed was planted using a no-till cone plot drill at a consistent planting depth of ~1 cm.

Experiment 2. Experiment 2 was conducted at RELREC on ~0.25 ha adjacent to Experiment 1, and was also established and managed according to USDA organic standards and was in transition to organic certification. To determine the effect of fall planting date on timing of spring cover crop flowering, flower density, and native bee visitation, three species of cover crop, canola, medium red clover, and Austrian winter pea were planted in monoculture on four dates during the fall of 2012, each three weeks apart. The first planting date (PD 1) occurred on 1 August, planting date two (PD 2) on 24 August, planting date three (PD 3) on 13 September, and planting date four (PD 4) on 5 October 2012. These variations in fall planting date are representative of a range of possible cover crop planting dates for use in common organic and conventional crop rotations of the Mid-Atlantic region. The experiment utilized a split-block design with crop and planting date as the main effects. Each whole plot was ~9 m by 11 m, with crop type as a whole plot main effect, and planting date as split plots of ~2 m by 11 m stripped within the whole plot. Each treatment was replicated four times with a total of 12 whole plots (cover crop type) and 48 split plots (planting date by cover crop type). For clarity, split plot treatments are subsequently referred to simply as treatment "plots" as a combination of crop type and planting date.

Seeds were weighed and measured to provide a seeding rate that was representative of common farmer practices for cover crop monocultures of each species (Clark 2007). Planting was completed using a no-till cone plot drill, which planted nine rows of seed, each 19 cm apart. Planting depth was varied by crop. Canola (12.7 kg/ha) and red clover (13.4 kg/ha) were planted at 1 cm depth and Austrian winter pea (87.3 kg/ha) was planted at 2 cm depth. Plots were managed without irrigation and with manual weed suppression as needed in the fall and early spring.

Floral Density and Phenology. *Experiment 1.* To assess duration of cover crop bloom across treatments, two randomly located 0.25-m^2 quadrats were flagged in each plot prior to the onset of flowering. One quadrat was located along a transect at the interface between the crop and a permanent, grassed drive row (edge) and the second along an inner, center-plot transect (center) ~12 m from, and parallel to, the drive row edge. All plots were monitored for open cover crop flowers at least once per week and the total number of open blooms and number of blooming plants were recorded for each quadrat from the onset of flowering in the treatments until the day prior to termination of the cover crops by moldboard plowing in preparation for planting of cash crops. Data collected from these stationary quadrats were used to observe plot phenology over time.

Six additional quadrats per treatment plot were monitored within 24 h of the observations to assess the pollinator community. These were randomly located along the edge and center transects, with three quadrats on each transect. For these observations, the total number of open blooms per 0.25m^2 was recorded to serve as a measure of average bloom density for the treatment across time. Data collected from these independently located quadrats were used as a floral density covariate in appropriate bee visitation analyses.

Experiment 2. To assess bloom phenology and density across cover crop species and planting date treatments, one randomly located, 0.25-m^2 quadrat was flagged in each plot prior to the onset of flowering. All treatments were monitored for open cover crop flowers, or flower heads for red clover, at least once per week and the total number of open blooms was recorded for each quadrat from the onset of flowering in the treatment until all blooms were gone or the termination of the experiment in early July. The total number of cover crop plants and number of plants in bloom were also counted in all canola treatment plots. Data collected from these stationary quadrats were used to observe plot phenology over time.

Additionally, three randomly placed quadrats per plot were monitored within 24 h of the pollinator observations. For these observations, the total number of open blooms per 0.25m^2 was recorded to serve as a measure of average bloom density for the plot across time. Data collected from these independently located quadrats were used as a floral density covariate in appropriate bee visitation analyses.

Pollinator Observations and Specimen Collection. *Experiment 1.* All bee visitation and behavior data values analyzed in this experiment are from a single date of 2 May 2013. Bee visitation data were also collected on 13 May 2013 but was excluded from visitation rate and pollinator behavior analyses as the air temperature averaged 5.4°C during morning data collection and 8.5°C for the afternoon collection. These temperatures were deemed too cold for sufficient bee foraging behavior and corresponded with very low insect activity. However, bee species data from 13 May was included in the total species richness by mixture treatment (Table 1), and in all plant and flower analyses.

As a method of quantifying abundance of visitation to the blooming cover crop, visual pollinator observations were conducted on two occasions after bloom initiation in canola and prior to cover crop termination in mid-May as was required for planting the corn as the next stage in this crop rotation. Each plot was visually monitored for bee floral visitation for 2 min per transect, twice per day, once in the morning (0900–1200 hours) and once in the early afternoon (1230–1530 hours). The observer walked at a slow and steady rate along the transect recording all bees that visited the open cover crop blooms during the 2-min period. Each bee that was observed landing on the reproductive parts of the flower was recorded to the lowest taxonomic level possible from visual estimations (modified from Westphal et al. 2008). Groups that were easy to determine on-the-wing were identified to genus (e.g., *Bombus*, *Apis*, *Xylocopa*), whereas those that were smaller or more difficult to identify in motion were

Table 1. Number of each bee species collected from hand-netting on each cover crop, cover crop mixture treatment, or in landscape-level passive traps from 22 April–2 July 2013

Bee species	Experiment 1			Experiment 2			Landscape-level traps				
	1 Sp.	4 Sp.	6 Sp.	Ca	AWP	RCl	Bl Vane	Y Vane	Bl Pan	Y Pan	Wh Pan
Agapostemon sericeus (Forster)	–	–	–	1	–	–	–	–	1	1	–
Agapostemon texanus Cresson	–	–	–	–	–	–	1	–	–	–	–
Agapostemon virescens (F.)	–	–	–	–	–	–	10	2	5	9	3
Andrena arabis Robertson	2	3	1	18	–	–	–	–	–	–	–
Andrena carlini Cockerell	1	–	–	3	–	–	–	–	–	–	–
Andrena commoda Smith	–	–	–	6	–	–	1	–	–	–	–
Andrena crataegi Robertson	–	–	–	3	–	–	–	1	–	–	–
Andrena cressonii Robertson	–	–	–	2	–	–	–	–	–	–	–
Andrena forbesii Robertson	–	1	1	4	–	–	1	–	–	–	1
Andrena hippotes Robertson	4	1	–	17	–	–	1	4	–	–	–
Andrena imitatrix Cresson	1	–	–	4	–	–	2	7	1	1	2
Andrena integra Smith	–	–	–	–	–	–	-	2	–	–	–
Andrena miserabilis Cresson	1	–	–	1	–	–	1	1	–	–	–
Andrena nasonii Robertson	–	–	–	19	–	–	2	–	–	–	–
Andrena perplexa Smith	–	–	–	4	–	–	1	–	–	–	1
Andrena rugosa Robertson	1	2	–	2	–	–	–	–	–	–	–
Andrena vicina Smith	–	–	–	3	–	–	–	–	–	–	–
Andrena wilkella (Kirby)	–	–	–	1	–	9	–	–	–	–	–
Apis mellifera[a] L.	6	2	–	4	2	–	4	1	–	–	–
Augochlorella aurata (Smith)	–	–	–	14	–	–	1	1	–	1	–
Bombus bimaculatus Cresson	–	–	–	1	14	17	23	–	-	–	–
Bombus fervidus (F.)	–	–	–	–	1	–	1	–	–	–	–
Bombus griseocollis (DeGreer)	–	–	–	–	3	2	–	–	–	–	–
Bombus impatiens Cresson	2	–	–	7	2	5	5	–	–	–	–
Bombus perplexus Cresson	–	–	–	–	–	–	2	–	–	–	–
Bombus ternarius Say	–	–	–	–	–	–	1	–	–	–	–
Bombus vagans Smith	–	–	–	–	3	1	7	–	–	–	–
Ceratina calcarata Robertson	–	–	–	1	–	–	–	–	–	–	–
Ceratina mikmaqi Rehan and Sheffield	–	–	–	–	–	–	1	–	–	–	–
Eucera atriventris (Smith)	–	–	–	–	–	–	1	–	–	–	–
Eucera hamata (Bradley)	–	–	–	–	–	–	38	–	3	–	–
Halictus confusus Smith	–	–	–	2	–	–	–	1	–	–	–
Halictus ligatus Say	–	–	–	1	–	–	6	1	22	13	5
Halictus rubicundis (Christ)	1	–	–	4	–	1	3	1	–	1	1
Hoplitis pilosifrons (Cresson)	–	–	–	–	–	–	1	–	–	–	–
Lasioglossum albipenne (Robertson)	–	–	–	–	–	–	2	–	1	1	1
Lasioglossum cinctipes (Provancher)	–	–	–	–	–	–	–	–	1	–	–
Lasioglossum coriaceum (Smith)	–	–	1	1	–	–	–	–	2	3	1
Lasioglossum forbseii (Robertson)	–	–	–	–	–	–	1	–	–	–	–
Lasioglossum foxii (Robertson)	–	–	–	2	–	–	–	–	–	–	–
Lasioglossum hitchensi Gibbs	2	–	–	7	5	–	6	–	2	–	–
Lasioglossum imitatum (Smith)	–	–	–	1	–	–	–	–	–	–	–
Lasioglossum leucozonium (Lovell)	–	–	–	–	–	–	–	–	2	4	–
Lasioglossum nymphaearum (Robertson)	–	–	–	3	–	–	1	–	1	–	1
Lasioglossum obscurum (Robertson)	–	–	–	1	–	–	–	–	–	–	–
Lasioglossum paradmirandum (Knerer and Atwood)	1	1	–	2	1	–	16	1	4	3	1
Lasioglossum pectorale (Smith)	–	–	–	1	–	–	3	–	–	–	–
Lasioglossum perpunctatum (Ellis)	–	–	–	1	–	–	3	1	–	2	1
Lasioglossum pilosum (Smith)	–	–	–	–	3	–	27	–	8	7	10
Lasioglossum tegulare (Robertson)	–	–	–	8	1	–	–	–	–	–	–
Lasioglossum timothyi Gibbs	–	–	–	–	–	–	–	–	–	–	1
Lasioglossum truncatum (Robertson)	–	–	–	2	–	–	19	2	4	2	1
Lasioglossum versatum (Robertson)	–	–	–	1	–	–	1	–	–	–	–
Melissodes sp.	–	–	–	–	–	–	1	–	–	–	–
Nomada sp.	–	–	–	–	–	–	–	1	–	–	–
Osmia bucephala Cresson	–	–	–	–	–	–	1	–	–	–	–
Osmia cornifrons (Radoszkowski)	–	–	–	–	–	–	1	–	–	–	–
Osmia sp.	–	–	–	–	–	–	1	–	–	–	–
Osmia taurus Smith	–	–	–	–	–	–	3	–	–	–	–
Sphecodes dichrous Smith	–	–	–	–	–	–	1	–	–	–	–
Xylocopa virginica[a] (L.)	–	–	–	5	15	–	2	–	–	–	–
Species Richness	11	6	3	36	11	6	40	15	14	13	14

1 Sp., canola monoculture treatment; 4 Sp., four-species mixture treatment; 6 Sp., six-species mixture treatment; Ca, canola; AWP, Austrian winter pea; RCl, red clover; Bl, florescent blue; Y, florescent yellow; Wh, white.

[a] *A. mellifera* and *X. virginica* were not collected at full quantity, as reliable species identification could be gained via visual observation; actual abundance may therefore be greater than shown.

grouped into morphospecies categories (e.g., large dark bee, green bee, small dark bee).

After completing the observations on the edge and center transect of each plot, both transects were walked for an additional 60 s and all bees observed landing on the reproductive parts of the cover crop flowers were collected with an aerial insect net. Netted specimens were killed using a glass kill jar with an ethyl acetate-soaked plaster bottom and returned to the lab. All bees were identified to species. These specimens served as a reference for the morphospecies categories of the preceding observation period as well as an overall indicator of the bee species richness associated with each treatment. As species richness, and not bee abundance, was the goal of collecting netted specimens, bees that were obviously of the same species (e.g., *Xylocopa virginica* (L.)) and that had been collected already once during the netting period on that treatment plot were not collected in duplicate, even if observed on the flowers of interest. *Apis mellifera* L. specimens were not collected often during netting periods, as species identification was confident during the visual observations.

Bee species were identified using a series of online or hard-copy taxonomic keys, as appropriate by genus or subgenus (Bouseman and LaBerge 1979, McGinley 1986, Gibbs 2011, Gibbs et al. 2013, Discover Life 2014). Species identifications were confirmed by Jason Gibbs, Dept. of Entomology, Michigan State University. Voucher specimens have been submitted to the Frost Entomological Museum at the Pennsylvania State University, University Park, PA.

Weather data including air temperature, 30 s average wind speed, and sky condition were collected twice for each session, before and after each morning and afternoon observation and netting period using a thermo-anemometer (Kestrel 2000, Nielsen-Kellerman, Boothwyn, PA). This was repeated for both the morning and afternoon observation sessions.

Experiment 2. Pollinator observation and netting was performed using the same protocol as in Experiment 1 with the exception that only a single observation or netting event was conducted per treatment plot in the morning and afternoon periods. In this case, the observer walked at a slow and steady pace around the perimeter of each plot collecting observation data or netting specimens. All Experiment 2 data were collected weekly from late-April to early-July, 2013.

Landscape-Level Passive Bee Collection. To compare the bee community collected from the flowering cover crops to the bee community in the landscape for both experiments, we placed two types of passive traps, pan and plastic vane traps, across the site on a weekly basis from 22 April 2013 until the completion of both experiments in this study. Traps were in place for 48 h with collected specimens removed from the traps every 24 h. Traps were placed in linear transect groups composed of three pan traps (one each white, yellow, blue) and two vane traps (one each blue and yellow). In total, eight groups of pan and vane traps were deployed across the full Experiment 1, 11 ha study area. All traps were located along grass access roads surrounding the study plots, and were as evenly distributed across the study area as was possible given road spacing constraints and other field operation concerns.

Methodology used for pan trapping was adapted from Westphal et al. (2008) and from *The Bee Inventory Plot* report (LeBuhn et al. 2002). The pan traps, also referred to as bee bowls, were constructed of 96-ml plastic soufflé cups spray-painted in white (Krylon Fusion for plastic, Cleveland, OH), florescent yellow (Krylon, Cleveland, OH), or florescent blue (ACE Glo Spray, Oak Brook, IL). All yellow and blue bowls were also painted with a primer of the white plastic-bonding paint. Bowls were mounted above the ground on 1.2 m tall, 2 cm diameter wooden dowels. Atop each dowel one painted bowl was attached using a single thumb tack. The final setup consisted of another bowl of the same color placed within the supporting thumb-tacked bowl. The sample bowl was filled three-fourths full with soapy water created using 2 liters of water and ~1 ml of nonscented dish soap.

The plastic vane traps (SpringStar Inc., Woodinville, WA) are constructed of yellow and florescent blue perpendicular vanes and a collecting tub attached below the vanes. All vane traps were used in their unaltered form. Each trap was suspended from a 1.2-m galvanized steel shepherd's hook purchased from a local garden supply store. Approximately 200 ml of soapy water mixture were added to the collection tub of each vane trap to act as an insect killing agent.

All nonbee insects collected in the traps were considered bycatch and discarded.

Statistical Analysis. Data analysis was performed with the R statistical language (R Core Team 2012) with additional R packages used for linear mixed-effects models (Bates et al. 2013) and Tukey's multiple comparison post hoc test (Hothom et al. 2008). Generalized linear mixed-effect models with a Poisson distribution were used for all bee visitation data analyses using random error variables appropriate for blocked or split-blocked designs. Appropriate temperature or wind speed covariates were used as determined by significant linear correlation between the environmental variable and the bee visitation rate for each treatment. Plant-based data analysis was performed using linear mixed models including random errors necessary for blocked designs and repeated measures analysis over the time span of each cover crop treatment. Correlations between individual variables were performed using simple linear regression.

Results

Experiment 1. Cover crop treatments were terminated by tillage on 14 May 2013. Due to limitations in spring growing period, canola was the only cover crop in the mixture treatments to achieve bloom prior to termination for organic field corn planting. A total of 23 bee species were collected over the course of Experiment 1; 13 species were collected from blooming canola in one of the three cover crop treatments, and 18 species from the landscape-level traps (data shown for landscape-level traps in table not separated by

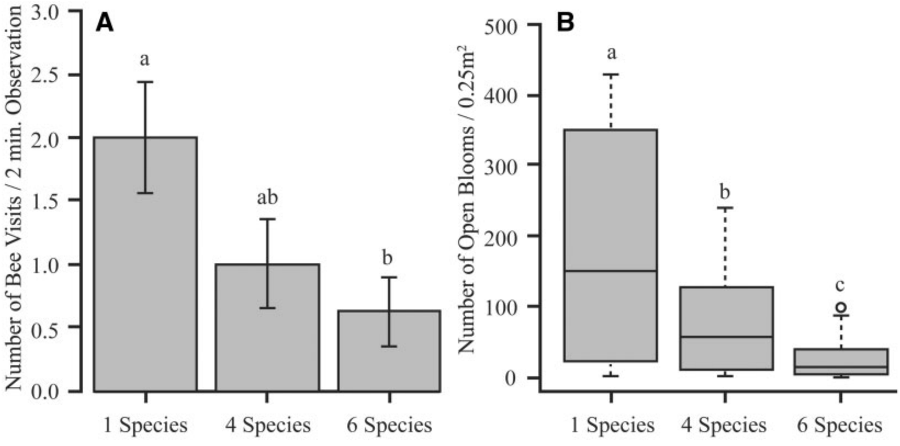

Fig. 1. (A) Average total bee visitation abundance per 2-min observation period. Error bars are standard error of the mean; $N = 16$. (B) Box and whisker plot of the number of open blooms per 0.25 m^2 by cover crop mixture treatment and across the total time span of the experiment. Bars and boxes that do not share the same letter are significantly different at $P < 0.05$ using Tukey's multiple comparison test.

experiment or date; Table 1). Of these, 10 bee species were unique to the landscape trap collections and were not recorded visiting the cover crop treatments. The greatest number of bee species were collected from the one species mixture treatment (canola monoculture) followed by the four species and six species mixture treatments, respectively (Table 1).

The observed bee visitation rates varied significantly by mixture treatment ($\chi^2 = 13.0$; df = 2; $P = 0.001$; Fig. 1A). Bee visitation rate was significantly greater in the one-species mixture treatment than in the six-species mixture ($P = 0.004$), with the four-species mixture demonstrating an intermediate level of bee visitation not significantly different from the one-species mix ($P = 0.061$) or the six-species mix ($P = 0.473$; Fig. 1A).

Across the three cover crop mixture treatments, there were significant differences in canola flower density, with the one-species mix being significantly greater than the four-species mixture ($P < 0.001$) and the six-species mixture ($P < 0.001$). Bloom density in the four- and six-species mixture treatments were also significantly different from each other ($P = 0.029$; Fig. 1B). Whereas the three treatments showed a significant trend in total canola plant density analogous to that of the canola flower density (data not shown), the canola monoculture plots had a significantly greater mean (± SE) number of blooms per blooming plant (6.5 ± 0.58) than either the four-species mixture (4.2 ± 0.44; $P < 0.001$) or six-species mixture treatments (4.8 ± 0.78; $P = 0.014$).

A significant, positive linear correlation was found between the number of open blooms (canola bloom density) and the number of observed bee visits ($F = 11.5$; df = 1,46; $P = 0.001$; $R^2 = 0.20$). Flower density was not included as a covariate in the general linear model for bee visitation rates due to the high correlation found between average flower density and mixture treatments ($F = 30.83$; df = 1,45; $P < 0.001$; $R^2 = 0.58$).

Experiment 2. A combined total of 61 bee species were collected from landscape-level passive traps and crop-level netting throughout the course of Experiment 2. A total of 36 bee species were collected in canola, followed by Austrian winter pea and red clover with 11 and 6 species, respectively (Table 1). In contrast, 49 bee species were collected in the landscape-level traps, 12 of which were unique to the traps and not collected on any of the three cover crops. No single crop or trapping method collected all species observed during the span of this experiment.

The three cover crop species not only varied in total bee species richness but also in bee community composition. Canola visitation was dominated by *Andrena* spp. and other small-bodied bees of the family Halictidae (Table 1). Austrian winter pea was visited by larger-bodied bumble bees (*Bombus spp.*), carpenter bees (*Xylocopa virginica*), and a few tiny *Lasioglossum* spp. (Table 1). Red clover, which supported the lowest total bee diversity, was primarily visited by bumble bees and *Andrena wilkella* (Kirby) (Table 1). In contrast, the most abundant species collected in the landscape-level traps were not only different than the most abundant species found on any cover crop, but two of the species collected in the highest numbers, *Eucera hamata* (Bradley) and *Agapostemon virescens* (F.), were not collected visiting any of the cover crops in this study (Table 1).

The three cover crop species differed significantly in bee visitation rates with significantly greater numbers of bees observed visiting canola than Austrian winter pea ($P < 0.001$) or red clover ($P < 0.001$). Red clover and Austrian winter pea did not differ in bee visitation rate ($P = 0.965$; Fig. 2).

Timing of the onset and duration of flowering and winter survival varied across cover crop species and planting dates. Canola was the earliest cover crop to bloom, followed by Austrian winter pea and red clover. The duration of flowering for canola and Austrian

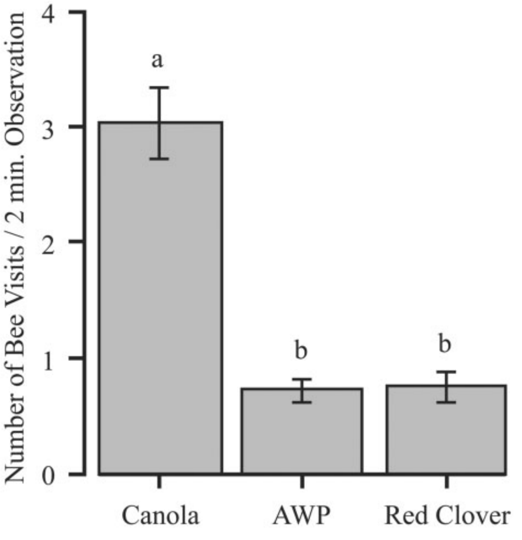

Fig. 2. Average number of bee visits per 2-min observation period (± SEM). $N = 139$ for canola, $N = 140$ for Austrian winter pea (AWP), and $N = 66$ for red clover. Bars that do not share the same letter are significantly different at $P < 0.05$ using Tukey's multiple comparison test.

winter pea, and between the peas and red clover overlapped for only a few days (Table 2). Each cover crop had at least one planting date treatment that resulted in poor winter survival. Overwintering success varied between cover crop species with canola and red clover showing limited winter survival in the treatments planted latest in the fall, whereas Austrian winter pea had limited winter survival for the first fall planting date (Table 2). Because experimental observations concluded on 8 July 2013, the true peak blooming dates for red clover planting dates one through three are unknown. Additionally the few surviving plants in red clover planting date four did not produce any flowers prior to the completion of the study.

There was a significantly lower bee visitation rate for canola planting date four than planting date one ($P = 0.002$), planting date two ($P < 0.001$), or planting date three ($P < 0.001$; Fig. 3A). Canola planting date four also had a significantly lower bloom density per $0.25\,m^2$ than in planting date one ($P = 0.003$), planting date two ($P < 0.001$), or planting date three ($P = 0.023$; Fig. 4A). In combination, we observed a significant, positive correlation in bee visitation rate with increasing canola flower density ($F = 26.0$; df = 1; $P < 0.001$; $R^2 = 0.16$).

There was significantly lower total canola plant density in planting date one (13.9 ± 2.76) than in planting dates two (30.8 ± 3.01; $P < 0.001$) or three (39.1 ± 5.82; $P < 0.001$) and between planting dates four (8.1 ± 1.69) and two ($P < 0.001$), and four and three ($P < 0.001$). However, no difference was found in plant density between planting dates one and four ($P = 0.633$) or two and three ($P = 0.110$). While planting date four had lower levels of flower and plant density, planting date one showed a total bloom density equal to that of the second and third plantings. This difference between low plant density and high flower density in planting date one is illustrated by a significantly greater number of flowers per plant in planting date one (15.0 ± 3.17) than in planting date two (7.66 ± 1.32; $P = 0.006$), planting date three (4.51 ± 0.70; $P < 0.001$), or planting date four (5.91 ± 1.32; $P < 0.001$).

For Austrian winter pea, there was a significantly lower bee visitation rate for the first planting date than for planting date two ($P = 0.008$), planting date three ($P = 0.002$), or planting date four ($P = 0.003$; Fig. 3B). In addition, the first planting date of Austrian winter pea had significantly fewer flowers per $0.25\,m^2$ than planting dates two ($P = 0.002$), three ($P < 0.001$) or four ($P < 0.001$; Fig. 4B). This relationship between lower bee visitation in the first planting date and average flower density is also demonstrated via a significant, positive correlation between number of bee visits per observation period and the average flower density ($F = 25.4$; df = 1,138; $P < 0.001$; $R^2 = 0.16$).

In red clover, there were more bees observed visiting the flowers of the first planting date of red clover than planting date two, although this difference was only marginally significant ($P = 0.052$); no bees were recorded on the flowers of planting date three (Fig. 3C). There were no significant differences in red clover flower head density between planting dates one and two ($P = 0.306$; Fig. 4C). The third planting date of red clover, which produced flowers only during the final week of the study (Table 2), had significantly fewer total clover heads than the first or second planting dates ($P < 0.001$ and $P < 0.001$; Fig. 4C). Planting date four was not included in these analyses, as no flowers were produced during the study. As with canola and Austrian winter pea, red clover also showed a significant, positive relationship between average flower density and bee visitation abundance ($F = 14.7$; df = 1,62; $P < 0.001$; $R^2 = 0.19$).

Discussion

Because many growers already plant cover crops to enhance a variety of ecosystem services, it is logical that capitalizing on a previously established farmer practice could help to increase adoption of flowering cover crops for pollinator conservation. In this scenario, farmers need only to adjust the species of cover crops used to include those that produce flowers visited by beneficial insects. This can likely be accomplished without negatively affecting the other field-level benefits achieved by planting cover crops, particularly if the cover crops are planted in diverse mixtures providing a range of ecosystem services. While the discussion about benefits to pollinators from flowering cover crops is not necessary novel (e.g., Mader et al. 2011), evidence given is often anecdotal and the scientific literature supporting these anecdotes is limited. Thus, to consider the use of flowering cover crops as a within-field conservation strategy for native bee communities, it is important to understand how cover crop species grow

Table 2. Dates of first recorded bloom, peak bloom, final bloom, and quality of winter survival for each cover crop species and planting date for Experiment 2

Crop	Planting date	First recorded flowers	Peak flowering	Last recorded flowers	Winter survival
Canola	1	April 21	May 12	June 3	Good
	2	April 28	May 12	June 3	Good
	3	May 6	May 22	June 3	Good
	4	May 21	June 3	June 19	Poor
AWP	1	May 28	June 11	July 1	Poor
	2	May 21	June 11	July 1	Good
	3	May 21	June 3	June 24	Good
	4	May 28	June 3	June 24	Good
Red clover	1	June 3	July 8[a]	n/a	Good
	2	June 3	July 8[a]	n/a	Good
	3	July 1	July 8[a]	n/a	Poor
	4	n/a	n/a	n/a	Poor

[a] Red clover was not monitored, and no data were collected after 8 July 2013. Therefore actual peak and end flowering dates are unknown.

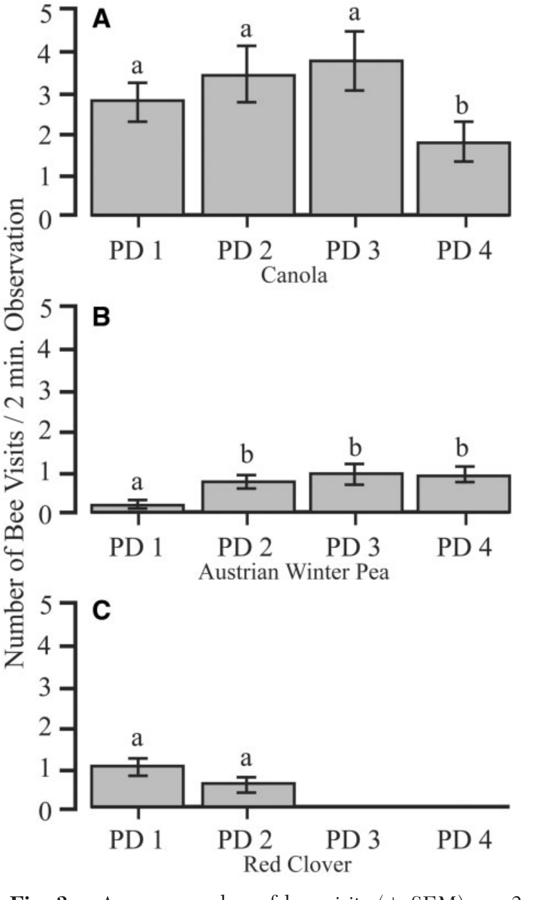

Fig. 3. Average number of bee visits (± SEM) per 2-min observation period in (A) Canola, (B) Austrian winter pea, and (C) red clover. Bars that do not share the same letter are significantly different at $P < 0.05$ using Tukey's multiple comparison test.

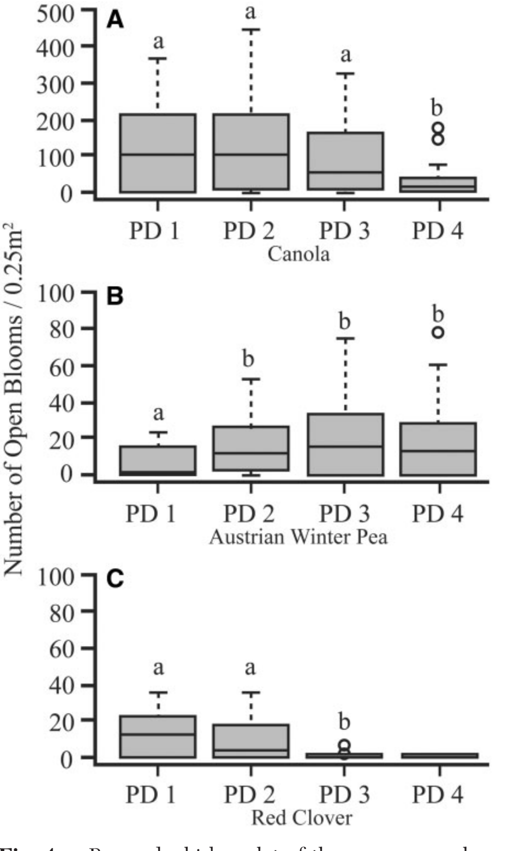

Fig. 4. Box and whisker plot of the average number of open blooms per 0.25 m^2 of (A) Canola, (B) Austrian winter pea, and (C) red clover planting dates (PD) across all weeks of the blooming period. Boxes that do not share the same letter are significantly different at $P < 0.05$ using Tukey's multiple comparison test. Red clover planting date four was not included in the analysis, as no flowers were present during study.

and produce floral resources within common rotation windows and under field conditions.

The goal of this study was to help bridge current knowledge gaps on how overwintering and flowering cover crop species respond to variations in common agronomic management practices, and how those practices may impact resource use by pollinators. Specifically, we focused on the influence of plant diversity, fall planting and spring termination times, and cover crop species selection on springtime floral resource quantity and subsequent native bee visitation.

The crop rotation window that was used for Experiment 1 is common for central Pennsylvania feed grain rotations. However, because of the restrictive nature of the time widow for planting corn in the Mid-Atlantic and other short-growing-season regions in the U.S., cover crops were terminated and incorporated into the soil in mid-May. While this time period was sufficient to achieve many of the field-level benefits from cover crops such as retention and provision of soil nutrients, weed suppression, or control of erosion, the rotation created a limited timeframe for cover crop flower production. Of the cover crop species used in this study, canola was the only crop that produced flowers prior to termination. Austrian winter pea and red clover, although present in both the four- and six-species mixtures, were terminated before flowering and thus provided no floral resource benefit to the pollinator community within this rotation window.

This field crop rotation window, however confined in scope due to limits in flower blooming time and weather conditions, did support the goal of providing early-season resources to the springtime native pollinator community in the year of this study. The first native bees were collected in the passive landscape-level traps on 22 April 2013, which corresponded closely to the date of first bloom of the canola cover crop. This observation provides evidence of the co-occurrence of active bee communities in the environment and the early-season cover crop resource.

In addition to the existence of appropriate floral resources in the environment during this early-season time period, Experiment 1 also focused on the effect of cover crop plant diversity on available floral resource quantity. We observed a significant decrease in flower density in the two mixture treatments compared to the monoculture treatment. This corresponded with an equally significant decrease in canola plant density, as would be indicated by decreased canola seeding rates, but a dissimilar pattern in the number of canola flowers per plant across the treatments. Canola flower density decreased linearly with plant density, but the canola grown in monoculture had significantly greater numbers of flowers per plant than in either the four- or six-species mixtures. Canola plants and their floral resources have been shown to be affected by competition with weedy plant species (Bijanzadeh et al. 2010). We suggest that interspecific competition with other cover crops in the mixture treatments had some level of negative influence on canola plant growth, as evidenced by the decrease in per-plant flower production. Similar results were observed in Experiment 2 for canola, where the first planting date had significantly more flowers per plant than did any of the other planting date treatments. As intraspecific crop density has also been shown to influence canola crop production, in this case we conclude that the increased fall growth period for planting date one resulted in selection for fewer, larger canola plants than in the later-planted canola treatments (Cresswell 2001).

Given the limitations in spring bloom production that occurred in Experiment 1, Experiment 2 was aimed at studying cover crop flowering outside the restrictions of a single crop rotation. By creating a gradient of fall planting dates and unrestricted spring blooming opportunity, each of these cover crops and their associated pollinator communities could be studied and modeled across a variety of potential cash crop rotation windows. The goal was to observe what influences these changes in fall planting times would have on cover crop winter survival and subsequent springtime bloom, as these both influence prospective pollinator floral resource use.

Experiment 2 focused on the same three flowering and overwintering cover crop species as Experiment 1: canola, Austrian winter pea, and red clover. In general, because individual bee species respond differently to variations in flower physiology and morphology (O'Toole and Raw 1991, Potts et al. 2003), we expected the pollinator communities to vary across the cover crop species. Additionally, because pollinator community structure is also influenced by seasonal phenology, differences in cover crop seasonal bloom periods would also likely influence bee visitation abundance and diversity (Bartomeus et al. 2011, Kimoto et al. 2012). Indeed, we did observe unique native bee communities visiting each cover crop species, although no significant difference in bee community was found between cover crop planting date treatments.

Planting date affects the flowering phenology of many agricultural crops, including canola for oilseed production (Major et al. 1975, Alessi et al. 1977, Teasdale et al. 2004, Adamsen and Coffelt 2005). Differences in day length, temperature, and accumulated growing degree-days are attributed as the major influences of crop growth across planting date gradients. While we did observe differences in fall plant growth across planting date treatments, with the exception of canola planting date four, planting date did not have a significant effect on spring flowering time for the cover crop treatments in Experiment 2. Instead, we saw the highest influence of planting date on winter survival, rather than the initiation and duration of bloom. As a result, observations of plant growth throughout the spring saw a convergence of crop growth and flowering densities across planting dates as the warm season progressed. This diminishing difference in plant growth across establishment gradients has also been observed in other oilseed and cover crop planting date trials (Lutman et al. 2000, Teasdale et al. 2004). Differences in winter survival, however, were cover crop species-specific. Canola and red clover displayed low survival in the latest planted treatments, and Austrian winter pea showed limited survival with the earliest planting date. This, in combination with the differences in spring blooming time and duration across species, demonstrates that the influence of both fall and spring management timing is cover crop dependent.

Besides being the only cover crop to bloom in the rotation used for Experiment 1, Experiment 2 demonstrated that canola also attracted the greatest diversity of bee species. In fact, canola flowers have been shown to be attractive to a wide diversity of pollinators including managed honey bees, native bees, and flies of the Syrphidae family (Free and Nuttall 1968, Jauker and

Wolters 2008, Mänd et al. 2010, Viik et al. 2012, Woodcock et al. 2013). Bee community composition was not, however, the only difference observed between cover crop species. We also observed significant differences among the cover crops in bee visitation abundance with significantly more bees visiting canola than either Austrian winter pea or red clover. Given that Austrian winter pea and red clover did not flower until late-May to mid-June, these cover crops would require either rotation windows with summer cash crop planting times or that portion of the cover crop be left in the field to achieve any pollinator floral resource benefit. We conclude that, of the three cover crops studied, canola would have the greatest potential for providing early-season resources for beneficial insects in spring rotation windows for the Mid-Atlantic or in regions with a similar climate regime.

While cover crop species influenced bee community use in Experiment 2, bee visitation differences were observed across planting date treatments within each cover crop as well as across the mixture treatments in Experiment 1. In both cases, bee visitation frequency was reduced when the flower density was significantly lower. For Experiment 1, the increased mixture diversity created a dilution of canola floral resources which corresponded with an overall decrease in bee visitation. Similarly, Experiment 2 showed lowest bee visitation on planting date treatments with the lowest level of winter survival and therefore the fewest number of blooming plants and flowers per area (e.g., canola planting date four, Austrian winter pea planting date one). We conclude that in both cases, floral resource density was the primary factor in the differential response of the bee community across treatments. This conclusion is supported by studies of pollination services in canola fields (Viik et al. 2012) as well as other plant diversity studies (Potts et al. 2003, 2009; Holzschuh et al. 2006; Tuell et al. 2008). Potts *et al.* (2009) showed, specifically, that an increase in total plant diversity (including many nonflowering plant and grass species) did not positively influence bumble bee abundance, but mixtures with an increase in density of flowering plants did. The cover crop mixtures studied in Experiment 1, although differing in total plant diversity, consistently had only one flower-producing species. This further supports the conclusion that flower density, and not plant diversity directly, was the main factor influencing the observed levels of bee visitation. We do not conclude, however, that cover crop mixtures are not beneficial for conservation purposes, especially if the ultimate goal of cover cropping is to maximize total ecosystem service benefits to both field-level crop productivity as well as ecosystem health. Rather, we are advocating for informed considerations of how agronomic management choices influence the complete cover cropping system and its multifunctional services.

We did not monitor pollen or nectar levels for any of the treatments in either study and thus did not directly quantify resource availability to the pollinator community. Instead, we focused on flower density as an indicator of this resource. While soil fertility and other management practices were consistent across the whole study, it is possible that pollen or nectar differences may have contributed to the variations in bee visitation observed across cover crop treatments, or even cover crop species. Specifically, because red clover was the only crop to show variations in bee visitation across planting dates that did not correspond with similar patterns in flower density, it is possible that floral resource quantity or quality may have had an influence.

Additionally, it is important to consider variations in weather patterns from year to year and their consequences on winter survival, plant growth, flowering, and insect use. For example, in preliminary data collected on cover crop bloom and bee visitation in the spring of 2012, canola bloomed as early as the first week of April in central Pennsylvania (Ellis, unpublished data). In contrast, the first blooms of 2013 did not appear until the fourth week of April. This difference would have been specifically evident in Experiment 1, as total canola bloom was still reduced due to termination timing. Assuming that corn would have been planted on the same date in both years, this difference in weather conditions would have greatly influenced the quantity of canola bloom in the environment in that rotation window. Indeed, other studies have shown great differences between canola oilseed crop production between study years, which were attributed mostly to variations in weather across multiple growing seasons (Lutman et al. 2000).

Weather variations do not only affect plant growth but also influence the timing of insect emergence and foraging activity. In general, the suitable weather conditions for pollinator activity is considered to be low wind, no rain, dry vegetation, and temperatures above 15°C (Westphal et al. 2008), with larger bodied bees (e.g., bumble bees) more adapted to foraging in colder temperatures than those with smaller body sizes (Heinrich 1979, Vicens and Bosch 2000). However, as springtime weather conditions in temperate systems are often unpredictable, differences in seasonal temperature or rainfall have the potential to reduce total bee use of a cover crop resource if foraging is limited by ambient weather conditions. Because early-season cover crop bloom will always be subject to fluctuations in spring weather, it is possible that cooler or wetter spring seasons may not provide the same potential resource use as other warmer, drier years.

Another significant result from this study is that no single trapping method or cover crop species was representative of the total bee community observed during this study. Instead, the 61 bee species observed were distributed across cover crops and various passive trapping types and colors. This further supports the results of other studies that highlight the need for multiple collection methods in order to sample complete pollinator communities in a given area (Cane et al. 2000, Westphal et al. 2008, Wilson et al. 2008).

Flowering cover crops have great potential as an agricultural conservation tool that can benefit both production and conservation goals. However, as evidenced by these experiments, increasing our knowledge about the applied use of cover crops for this purpose requires a more complete understanding of the factors that can influence the timing, availability, or quantity of the floral resource. These experiments do not provide definitive answers about selecting the "proper" flowering cover crop for a particular rotation. Rather, they highlight the importance and influence of factors such as cover crop diversity, fall planting date, spring termination time, inter- and intraspecies competition, and cover crop species selection on potential floral resources. While future study is necessary before we have a complete understanding the utility of cover crops as a tool for pollinator conservation in annual, temperate cropping systems, this study will serve as a baseline for supplementary studies and as an indicator of relevant factors that conservationists and land managers must consider to successfully expand and refine the use of flowering cover crops in conservation agriculture.

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