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RESTORATION ECOLOGY
The Journal of the Society for Ecological Restoration

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RESEARCH ARTICLE

Pollinator planting establishment and bee visitation are influenced by seeding rate and post-seeding management

Jacquelyn A. Perkins[1,2], Jenna Walters[1], Logan Rowe[1], Julia Brokaw[1,3], Lauren Gedlinske[4], Elisabeth Anderson[1], Sichao Wang[5], Rufus Isaacs[1,6]

Perennial wildflower plantings are commonly used to support pollinators and other beneficial insects, but their establishment can be costly, and few studies have directly compared the effectiveness of different management strategies for wildflower establishment. To determine the relative importance of pre-seeding weed control, seed density, and post-seeding management on seed mix establishment, we developed a multifactorial field experiment in a grass-dominated weed community. Pre-seeding management treatments (mowing, herbicide, or soybean cover crops) did not affect the stem density of sown plants, or the percent of ground covered by sown plants. However, the percent of ground covered by weeds was significantly influenced by pre-seeding treatments, with infrequent mowing resulting in significantly less weedy ground cover than the herbicide or soybean pre-seeding treatments. Plots with a higher seeding rate had a significantly greater density of sown wildflower species and a higher percent cover of these species after 3 years. Plots that received no post-seeding management had higher stem density, a greater percent ground cover of sown forbs, and higher species richness compared to those that were intensively managed (mow or mow + herbicide). The total number of bee visits (honey bees, bumble bees, and other wild bees) increased with higher forb species richness, higher ground cover of sown forbs, and higher sown species richness. Doubling the density of seeds resulted in a 24.3% increase in the number of wild bees observed. When establishing wildflower habitat for pollinators, investment in ground preparation and seeding density has the greatest impact on sown species establishment.

Key words: bees, conservation, floral resources, habitat, native plants, pollination, restoration

Implications for Practice

- Seeding density is an important consideration when establishing pollinator habitat; an increased seeding rate can lead to significant increases in bee visitation to wildflower habitats.
- Restoration efforts can avoid spending time and resources on intensive post-seeding management such as mowing and spot spraying, as minimal post-seeding management can result in higher wildflower stem density, higher species richness, and greater ground cover of sown forbs.
- Investment in high seeding rate and pre-seeding site preparation during the establishment of pollinator planting is essential to achieve productive, species-rich pollinator plantings in grass-dominated areas of the Great Lakes region of the United States.

Introduction

Wildflower plantings are a common conservation strategy to promote biodiversity in agroecosystems (Blaauw & Isaacs 2014; Grass et al. 2016; Lowe et al. 2021). These plantings are installed to provide nutritional and nesting resources for pollinators throughout the season, which help to promote pollinator diversity and abundance on local (Garibaldi et al. 2014; Lowe et al. 2021; Scheper et al. 2021) and landscape (Jönsson et al. 2015) scales. This conservation practice can be incorporated into farms to support bees and other pollinating insects (Carvell et al. 2021; Graham et al. 2021), as well as natural enemies (Blaauw & Isaacs 2015; Campbell et al. 2017; Hatt et al. 2017), and birds (Pywell et al. 2012). Furthermore,

Author contributions: RI, JB conceived idea and secured funding; RI, LR, JB, LG, EA designed methodology, applied early treatments; JAP managed the post-seeding treatments, led the writing of the manuscript; JAP, LR, JW collected the data; SW conducted statistical analysis; all authors contributed to manuscript drafts.

[1]Department of Entomology, Michigan State University, East Lansing, MI 48824, U.S.A.
[2]Address correspondence to J. A. Perkins, email albertj9@msu.edu
[3]Current address: Department of Entomology, University of Minnesota, St. Paul, MI 55108, U.S.A.
[4]Department of Ecology, Montana State University, Bozeman, MT 59717, U.S.A.
[5]Center for Statistical Training and Consulting, Michigan State University, East Lansing, MI 48824, U.S.A.
[6]Ecology, Evolution, and Behavior Program, Michigan State University, East Lansing, MI 48824, U.S.A.

doi: 10.1111/rec.14179
Supporting information at:
http://onlinelibrary.wiley.com/doi/10.1111/rec.14179/suppinfo

wildflower plantings may benefit surrounding natural systems through soil stabilization (Bretzel et al. 2009), reduction of pesticide and fertilizer run-off (Aldrich 2002; Wratten et al. 2012), and increased carbon sequestration (Weißhuhn et al. 2017; Ruf & Emmerling 2020). Placing wildflower plantings alongside crop fields or replacing crop areas with wildflower habitat has the potential to increase revenue for farmers through greater pollination (Morandin & Winston 2006; Garibaldi et al. 2014; Albrecht et al. 2020) due to spillover where bees attracted to wildflowers will also forage on neighboring crop flowers (Carvalheiro et al. 2012; Jönsson et al. 2015; Lowe et al. 2021). The establishment success of these plantings and their ability to support pollinator populations is highly variable due to many factors, including weed pressure, seed mix design, and the investment in pre- and post-seeding management, such that the resulting planting often does not match the seed mix used during establishment (Brudvig et al. 2017).

Weed pressure, seed mix design, and investment in pre- and post-seeding management all influence both the economic costs and ecological outcomes of restoration. Agricultural landowners will often choose to establish wildflower plantings in areas that are unsuitable for crop production (Carvell et al. 2006; Carvalheiro et al. 2012; Campbell et al. 2017). Oftentimes, these areas have high weed pressure, which can greatly limit the establishment of native flower species through intense competition (Washburn & Barnes 2000; Aldrich 2002; Williams et al. 2007). Intensive ground management prior to seeding wildflowers and intensive post-seeding management are recommended, but both can require significant financial investment, which may limit adoption (Hofmann & Isselstein 2004; Angelella et al. 2019). Government programs to support the establishment of pollinator habitats have broad support from the public (Hall & Steiner 2019; Nicholls et al. 2020); however, the costs and perceived success of wildflower establishment in achieving conservation goals can significantly impact the motivation of land managers to adopt and maintain habitat-enhancing management practices (Scheper et al. 2021). While there is a clear interest and incentive for establishing wildflower plantings among farmers, land managers, and government agencies, the costs of establishment remain a barrier. Because of this, more research is required to develop clear guidance on management practices that help to ensure the success and continuation of these habitat enhancement efforts, while also considering the economic costs.

With multi-million-dollar investments in pollinator habitat, it is important that these habitats are established in ways that are cost-effective while also reliably achieving the desired pollinator conservation outcomes (Bloom et al. 2021). Effective plant establishment requires an understanding of how best to prepare land for seeding, what seed density to use, and how to manage the site after establishment. The goal of pre-seeding management is to prepare seed beds for optimal germination and establishment of sown species by limiting competition with weeds (Aldrich 2002; Alignier & Baudry 2015; Angelella & O'Rourke 2017). Different approaches can be used to accomplish this, including mowing, herbicide applications, cover crops, or some combination of these (Aldrich 2002; De Cauwer et al. 2005; Carvell et al. 2021). However, optimal wildflower site preparation recommendations are variable (Aldrich 2002; Angelella & O'Rourke 2017), and only a few studies have directly compared the effectiveness of these different pre-seeding strategies for plant establishment (Frances et al. 2010; Angelella et al. 2019).

Optimizing seeding rates is another important management strategy to consider (Aldrich 2002; Frances et al. 2010). When seeding rates are too low, the establishment of desired plants may be limited, allowing weedy or undesirable plants to invade (Frances et al. 2010; Larson et al. 2011; Carter & Blair 2012). When seeding rates are too high, the cost of seeds can be prohibitive (Jackson & Meissen 2019; Schmidt et al. 2020; Goldsmith et al. 2021) and there is potential for lower long-term plant establishment due to density-dependent effects (Long et al. 2014; Wilkerson et al. 2014; Meissen et al. 2020). Yet, seeding wildflowers at a high rate is still recommended for optimal plant establishment (Dickson & Busby 2009; Barr et al. 2016; Jaksetic et al. 2017). Identifying affordable and effective seeding rates will be important for continued implementation of restoration activities that allow for maximum area of land conversion to pollinator habitat.

Post-seeding management aims to maintain or enhance the long-term quality of wildflower plantings (Kirmer et al. 2018). These post-seeding management approaches are used to mitigate unwanted plants from encroaching on wildflower plantings, as well as encourage the growth of newly sown plants (Fritch et al. 2011; Angelella & O'Rourke 2017; Glidden et al. 2021). Techniques used to accomplish this include mowing, herbicide spot treatments, or a combination of these at varying levels of intensity and frequency (Aldrich 2002; Kirmer et al. 2018). Mowing is frequently employed to reduce competition for light (Kirmer et al. 2018), and spot-spraying with herbicides is used to control weeds in established wildflower plantings, although the efficacy can be variable (Aldrich 2002). High labor and financial costs pose a considerable challenge to managing wildflower plantings during plant establishment (Aldrich 2002; Kirmer et al. 2018; Angelella et al. 2019), and the relative importance and response to these different inputs is inconsistent. While some studies describe positive outcomes following mowing (Hofmann & Isselstein 2004; Fritch et al. 2011) or herbicide applications (Aldrich 2002; Angelella & O'Rourke 2017), others have reported negligible or even negative consequences of post-seeding management in wildflower plantings (Washburn & Barnes 2000; Norcini et al. 2003; Frances 2008;). Recommendations for post-seeding management should be informed by comparative studies assessing the costs, time, and labor required, as well as outcomes for plants and pollinators.

Research-driven insights from comparing various pre-seeding, seeding, and post-seeding strategies in wildflower plantings are crucial for the successful implementation of these conservation efforts. To address this, we developed a multi-year field experiment to determine how pre- and post-seeding management strategies interact with seeding rate to influence metrics of plantings establishment, including wildflower species stem density, stem densities for three focal species, ground cover of sown forbs and weeds, and species richness of sown native species. We also evaluated how these various management strategies affect visitation by honey bees, bumble bees, and other wild bees. We hypothesized that the high seeding rate would positively impact wildflower establishment and subsequent bee visitation, and that the different management interventions during pre- and post-seeding would further influence planting establishment.

Methods

Plot Establishment and Management

This study was conducted in a 0.4 ha field at the Michigan State University Clarksville Research Center (Clarksville, Michigan). The site has a slight slope downward toward the west, and there was a fence around the site to prevent deer herbivory. Soils in the area are "Lapeer sandy loam" with 2–12% slopes and moderate erosion (USDA Natural Resources Conservation Service). Prior to the study, the field was a grass-dominated pasture with minimal mowing and no other management. No irrigation was applied prior to or during the experiment. In spring 2017, we established 96 plots that were each 3.5 × 2.7 m and separated by 3 m on all sides. The plots were randomly assigned a combination of pre-seeding, seeding, and post-seeding treatments, with 24 unique combinations (see Figs. S1 & S2). Each treatment combination was replicated four times. Pre-seeding treatments were implemented in spring and summer 2017, and seeding was completed in fall 2017. Post-seeding treatments were applied during the 2018 and 2019 growing seasons. Vegetation in the grassy drive lanes between plots was kept short throughout the experiment by mowing every 2–4 weeks as needed.

In spring 2017, each plot received one of the following pre-seeding treatments during the growing season (July–September) using a completely randomized design: (1) "frequent mowing" twice per month to maintain low vegetation height (mower deck set to 2 in.), (2) "infrequent mowing" once per month to maintain high vegetation height (mower deck set to 5.5 in.), (3) "herbicide" applications (glyphosate 2% concentration applied once per month in summer), or (4) "soybean" cover crop using Roundup Ready seed with glyphosate spot spraying once per month. In early October 2017, all plots were sprayed with glyphosate (2% concentration solution) to kill weeds and prepare for seeding. We randomly selected a 0.5 m^2 area (18.2 × 274.3 cm) within each plot in spring 2017 to establish a permanent quadrat for repeated vegetation assessments. These permanent quadrats were marked with a brightly colored metal washer nailed into each corner to allow us to find them in subsequent years, either visually or with a metal detector. The placement of the permanent quadrats started between 2 ft (0.6 m) from the north border of the sample plot, and 11 ft (3.4 m) from the north edge to minimize edge effects in sampling.

Wildflower seed mixes were applied in the late fall of 2017 by hand broadcasting a seed mix onto each plot at either a "low" (6 lbs/acre, equivalent to 323 seed/m^2) or "high" seeding rate (12 lbs/acre, equivalent to 646 seeds/m^2) with the seeding rate randomized evenly across the four pre-seeding treatments. We designed the seed mix to meet the minimum requirements of the USDA Conservation Reserve Program's CP42 Pollinator Habitat program at both the "low" and "high" seed rates (USDA Farm Service). The seed mix consisted of 15 forb species, 1 legume species, and 3 grass species, and the ratio of each species (by weight or seed count) was maintained in both seed rate treatments (Table S1). Species were selected to provide habitat and floral resources for pollinators from early spring to late fall in accordance with CP42 standards, and to promote bee abundance and diversity based on data from previous research in Michigan (Tuell et al. 2008; Rowe et al. 2018). At the time of purchase, the cost per acre for the low and high-rate seed mixes were \$382 and \$764, respectively. All seeds were sourced from the Michigan Wildflower Farm in Portland, Michigan.

Post-seeding management occurred in the growing seasons of 2018 and 2019. Within the plots that received the eight combinations of pre-seeding treatment and seeding rate, plots were randomly selected to receive one of the following post-seeding ground cover management strategies to be implemented during 2028 and 2019 (see Fig. S2): "mow" (1×/month), "mow + herbicide" that received 1×/month mowing and spot sprays with glyphosate, or "no management."

Vegetation Assessments

To measure the establishment of the plant community, we conducted whole plot assessments and quadrat assessments in June (early) and September (late) 2018–2020. For permanent quadrat locations, we located the metal washers and used a quadrat of the same dimensions placed over the area, allowing for accurate repeated plant surveys in the same location of each plot. Within each quadrat, the total number of plant stems for each sown forb and sown grass species was counted (if large enough to accurately identify). Additionally, each quadrat was assessed for percent bare ground, sown forbs, weedy forbs, sown grasses, and weedy grasses. In 2020, only a late-summer quadrat survey was conducted due to restrictions caused by the coronavirus disease 2019 pandemic. Plants were identified using Newcomb (1989) and the University of Michigan's herbarium website. Plants were identified to the lowest possible taxonomic level, and those that could not be identified to species with certainty were only identified to genus (e.g. *Solidago* spp.). Whole plots were assessed by an observer standing at the center of the long edge of each plot, who recorded the percent ground cover of bare ground, sown forbs, unsown forbs, sown grass, and unsown grass in the entire plot.

Additionally, we selected three focal flowering plant species to explore in more detail how the varying management strategies affected them. *Coreopsis lanceolata*, *Monarda fistulosa*, and *Symphyotrichum novae-angliae* were chosen because they are common in seed mixes, attractive to bees, have distinct flower morphologies, and represent different seasonal bloom phenologies, as well as representing early to late successional establishment. These three species were also dominant members of the floral community that was established throughout this study.

Pollinator Visitation

In summer 2020, we conducted timed observations of bees and other flower-visiting insects in each plot. These were done once a month through the growing season (June–September). Each plot was observed for 4 minutes by one observer, during which the individual insects observed visiting flowers within the plot were counted and recorded. Pollinators were counted if they were observed landing on the flowers within the plot. Observed pollinators were organized into the following groups: honey bees, bumble bees, and other wild bees (including carpenter bees, small black bees, large black bees, small green bees, and large green bees) (The Xerces Society 2014).

Statistical Analysis

All statistical analyses were conducted using the R statistical language (The R foundation) using packages glmmTBD (Brooks et al. 2017), performance (Lüdecke et al. 2021), emmeans (Lenth et al. 2023) and with data presented using ggplot2 (Wickham 2010). Due to the relatively low replication in this experimental design, we focused our analysis on the main effects of the three treatments. The fixed factors in the model were the pre-seeding treatments, seeding rate, or post-seeding treatments. These were examined as main effects and as interactions among the factors. For forb and weed cover data, the timing of assessment was also considered a fixed factor for repeated measurements in the plots. Final models were chosen based on AICc values (Akaike information criterion corrected for small sample size, AICc). When AICc was less than 2 between two nested models, a likelihood ratio test was used to determine the final model; see Tables S2-S9 for more details on model selection. Model assumptions were checked by examining plots of residuals versus fitted values. The Tukey HSD (honestly significant difference) method was used to correct multiple comparisons and control the family-wise Type 1 error at 0.05.

Negative binomial models were fitted to account for overdispersion, which was necessary for stem count data, and all wild bee count data. Hurdle models were fitted for honey bee and bumble bee data to compare among the treatments due to excess 0 counts beyond the capabilities of the Poisson model (Potts & Elith 2006). Generalized linear mixed models with a beta error distribution family and logistic link were fitted for forb and weed cover data. Early season and late season samples within each year from 2018 to 2020 were treated as discrete time variables to examine the trends of ground cover changes over time (six categorical levels, one factor). Compound symmetry covariance structure was incorporated into the model for forb cover data, to account for correlation due to repeated measures. First order autoregressive structure was incorporated into the model for weedy cover data to account for repeated measurements. Pearson's product moment correlation coefficient was calculated to examine the linear relationships between total bee visits and the various metrics of plant establishment success.

Results

We found that the different pre-seeding, seeding, and post-seeding management treatments resulted in statistically different plant establishment (depending on the metric used) and subsequent bee visitation. See Table 1 for a full summary of the chosen models and statistical significance.

How Do Pre- and Post-seeding Management Interact With Seeding Rate to Influence the Establishment of Wildflower Species?

During the first year after seeding (2018), the plots receiving the high seeding rate had an average of 12.71 ± 1.0 sown species per quadrat, which was significantly higher than the 9.46 ± 0.8 sown stems per quadrat found in plots with the low seeding rate ($p = 0.012$), regardless of pre-seeding management treatments. Plots that received the high seeding rate had faster establishment, with a total of 326 stems of sown forbs, which was 13.6% higher than the 287 total sown stems in quadrats from the low-seeded plots. *Chamaercrista fasciculata* total stem counts were 166.7% higher in no management plots compared to the mow treatment, and this effect was most pronounced in the initial establishment year (2018). In the final year of sampling (2020), the high seeding rate resulted in 21.7% more stems per plot on average than the plots with the low seeding rate. During the final year of the study (2020), the highest sown stem counts were observed in plots that received the pre-seeding herbicide treatment coupled with the high seeding rate (28.2 ± 4.4 stems per quadrat), followed closely by plots that received frequent mowing during the pre-seeding period and high seeding (27.1 ± 4.3 stems per quadrat) (Table 2; Fig. 1). However, pre-seeding treatments had no significant effect on the 2020 stem counts ($p = 0.535$). There was statistically significant variation among the post-seeding treatments for the total sown species stem counts in 2020 ($p < 0.001$), with the no management plots having significantly more stems than the mow and mow + herbicide treatments. Initial establishment of sown forb species in 2018 was more successful in the no management plots, with 27.8% higher stem counts in quadrats compared to mow and mow + herbicide. In the final year of the study (2020), the no management treatment had 45.8 and 66.7% more sown forb stems compared to the mow and mow + herbicide treatments, respectively (Fig. 1). See Tables S2 and S3 for full the deviance table.

How Do the Different Treatment Combinations Affect Stem Counts of Three Focal Species?

The establishment of *Coreopsis lanceolata*, *Monarda fistulosa*, and *Symphyotrichum novae-angliae* varied over time and pre/-post-seeding management treatments. Stem counts of *C. lanceolata* increased through the initial establishment years of the study but declined during the final sampling year (2020). Plots that received the frequent mowing pre-seeding treatment had the highest stem counts of *C. lanceolata* throughout the study, however, the number of stems still declined with this treatment during 2020. The no-management post-seeding treatment resulted in the highest *C. lanceolata* stem counts

Table 1. Summary table showing each response variable and the *p* values of each model chosen using the AICc approach. Bold values indicate a significant interaction, "—" denotes the term was not included in the fitted model.

	Fit models							
Response variable	*Pre-treatment*	*Seeding*	*Post-treatment*	*Pre-treatment × seeding*	*Post-treatment × seeding*	*Pre-treatment × Post-treatment*	*Pre-treatment × seeding × post-treatment*	*Time*
Total stem count in 2018	—	**0.012**	—	—	—	—	—	—
Total stem count in 2020	0.535	0.098	**<0.001**	**0.015**	—	—	—	—
Forb coverage %	—	**0.002**	**<0.001**	—	—	—	—	**<0.001**
Weed coverage %	**0.002**	**0.026**	**<0.001**	—	—	—	—	**<0.001**
Species richness	—	**0.038**	**<0.001**	—	—	—	—	—
Honey bee count	—	—	**<0.001**	—	—	—	—	—
All wild bees	—	**0.003**	**0.003**	—	—	—	—	—
Bumble bee (presence/not)	—	—	0.127	—	—	—	—	—

during early plot establishment, but this also resulted in very few stems of this species during the final sampling year.

Stem counts of *M. fistulosa* and *S. novae-angliae* both increased over time regardless of pre-seeding treatment, with the soybean pre-seeding treated plots showing the greatest stem counts of these two focal species in 2020. The plots that received the no management post-seeding treatment also resulted in the highest *M. fistulosa* and *S. novae-angliae* stem densities compared to the mow and mow + herbicide post-seeding treatments. Seeding rate also influenced the stem count of our focal species in 2020, with each species showing better establishment in the high seeded plots. *Monarda fistulosa* had 30.8% more stems, *C. lanceolata* had 41.8% more stems, and *S. novae-angliae* had 77.5% more stems per quadrat when compared to the low seeded plots.

Coreopsis lanceolata also benefited from the no management treatment, with 45.5% more total stems compared to the mow or mow + herbicide treatments in 2020. The no management treatment also had an 81.4 and 171.4% higher abundance of *M. fistulosa* and *S. novae-angliae* stems, respectively, in 2020 compared to the mow + herbicide treatment (Figure S3).

How Does Plot Management Influence Sown Forb and Weed Cover Over Time?

The percent ground cover of sown forbs in each whole plot increased over time, with fluctuations among the sampling times within each year and among the different treatment combinations (Figures S4 and S5). Pre-seeding treatment did not affect the percent of ground covered by sown forbs ($p = 0.185$). Throughout the study (data from 2018 to 2020), the percent of ground covered by sown forbs was significantly different between the seeding rates, with the high seeding rate at 27.7% cover compared with 23.0% for the low seeding rate ($p = 0.0016$). Plots receiving no management after seeding had significantly greater percent ground cover of sown forbs compared to the mow and mow + herbicide plots ($p < 0.001$), with an average of 30.4% sown forb cover compared to 22.6% in the mow treatment and 23.3% in the mow + herbicide treatment. There was no statistical difference in sown forbs cover between the mow and mow + herbicide treatments ($p = 0.67$) (more details in Tables S4–S7).

Weed ground cover generally decreased over time as the percent coverage of sown forbs increased, although this was highly variable between sampling periods. Across the study years, high seeding rate plots had 14.0% lower weedy ground cover than low seeding rate plots ($p = 0.026$). Weedy ground cover was also significantly affected by pre-seeding management ($p = 0.002$), with plots having infrequent mowing with significantly less weedy ground cover (34.7%) when compared to the herbicide (47.9%) or soybean (47.8%) treatments ($p = 0.001$). Comparing among the post-seeding treatments, the plots receiving mow + herbicide had significantly more weedy ground cover than plots with no management during the post-seeding period ($p < 0.001$). Plots with the mow treatment (without herbicide spot spraying) had 29.4% higher weed cover than those with no management ($p = 0.003$). There was no significant difference in weedy ground cover between mow and mow + herbicide treatments ($p = 0.127$).

Table 2. Estimated mean, standard error and 95% CI of the sown forb stems per sample in 2020 for all treatment combinations of pre-seeding and seeding rate during establishment of wildflower communities. Final model was chosen based on AICc scores.

Pre-seeding	*Seeding rate*	*Estimated mean ± SE stem count per 0.5 m²*	*Conf. low*	*Conf. high*
Herbicide	Low	19.3 ± 3.25	13.8	26.9
Soybean		20.0 ± 3.22	14.5	27.6
Infreq. mowing		21.0 ± 3.27	15.3	28.9
Frequent Mowing		15.3 ± 2.53	11.0	21.3
Herbicide	High	28.2 ± 4.43	20.6	38.5
Soybean		21.1 ± 3.38	15.3	29.0
Infreq. mowing		14.0 ± 2.33	10.1	19.5
Frequent mowing		27.1 ± 4.27	19.8	37.2

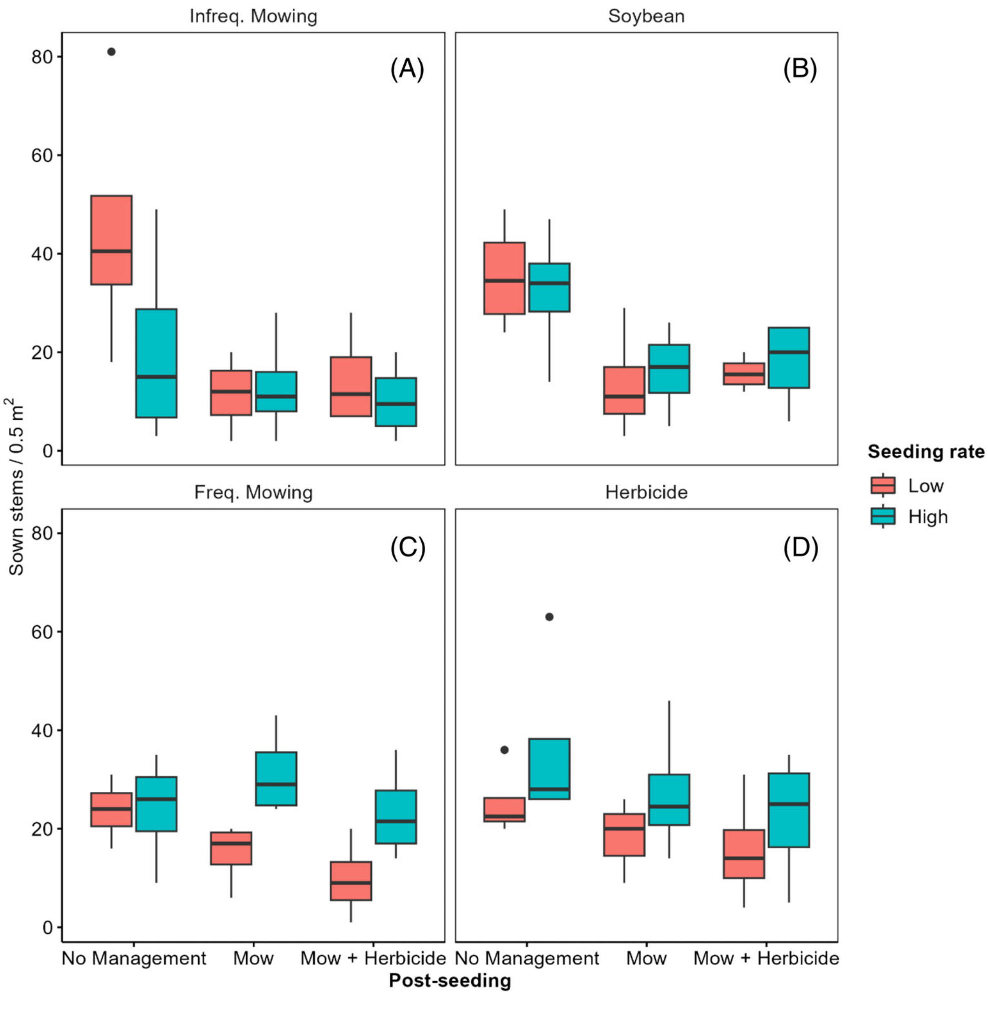

Figure 1. Total stem count in the final year of establishment (2020) for all sown forbs species in plots receiving each of the four pre-seeding treatments, and the subsequent post-seeding treatments. Colors represent the seeded density within each management treatment.

How Does Plot Management Affect Species Richness of Sown Wildflowers?

Seeding rate and post-seeding management had the greatest effects on the number of sown wildflower species in each plot in 2020. Those with the high seeding rate had an average of 4.32 ± 0.3 sown species per quadrat in 2020, which was 19.2% more sown species per quadrat than plots receiving the low seeding rate ($p = 0.039$). Plots with no management after seeding had an average of 5.31 ± 0.41 sown species present in 2020, which was significantly higher than plots receiving the mow treatment (3.55 ± 0.34 sown species, $p = 0.001$) or the mow + herbicide treatment (3.11 ± 0.31 sown species,

$p < 0.0001$). There was no significant difference in the number of sown species between the mow or mow + herbicide treatments in 2020 ($p = 0.34$) (Fig. 2).

How Do Different Types of Bees Respond to Establishment Treatments?

The total number of bee visits observed per plot in 2020 (sum of all honey bees, bumble bees, and other wild bees) was positively correlated with the various metrics of plant establishment for the sown wildflower species in the seed mix (Figure S6). This pattern was observed when measured as stem counts of sown forbs ($r = 0.31$, $t = 3.1$, $p = 0.002$), percent ground covered by sown forbs ($r = 0.34$, $t = 3.5$, $p < 0.0001$), or the species richness of sown forb species present ($r = 0.24$, $t = 2.4$, $p = 0.02$). As the sown species richness increased, observations of the various groups of bees also increased (honey bees $r = 0.18$, bumble bees $r = 0.17$, and wild bees $r = 0.22$). The correlation was statistically significant between sown species richness and all wild bees ($p = 0.04$); however, the relationship was not significant for honey bees or bumble bees ($p = 0.08$ and $p = 0.09$, respectively).

The specific management treatments compared in this study affected the number of honey bees and all wild bees (including bumble bees) observed visiting plots (Fig. 3). Honey bees were most responsive to the post-seeding management activities rather than pre-seeding or seeding rate. Plots that received no management after seeding had significantly higher honey bee abundance than plots that received mow or mow + herbicide treatments ($p = 0.008$ and $p < 0.0001$, respectively). Logistic regression models of presence/absence for bumble bee visitors in plots show that the best model for predicting the probability of bumble bees included the post-seeding treatments; however, this was still not a significant factor in predicting bumble bee observations in plots. Those plots receiving the most intense post-seeding management (mow + herbicide) had the lowest average observations of bumble bees, although this was not statistically significantly different from mow or no management ($p = 0.127$) (Figures 3 and S7).

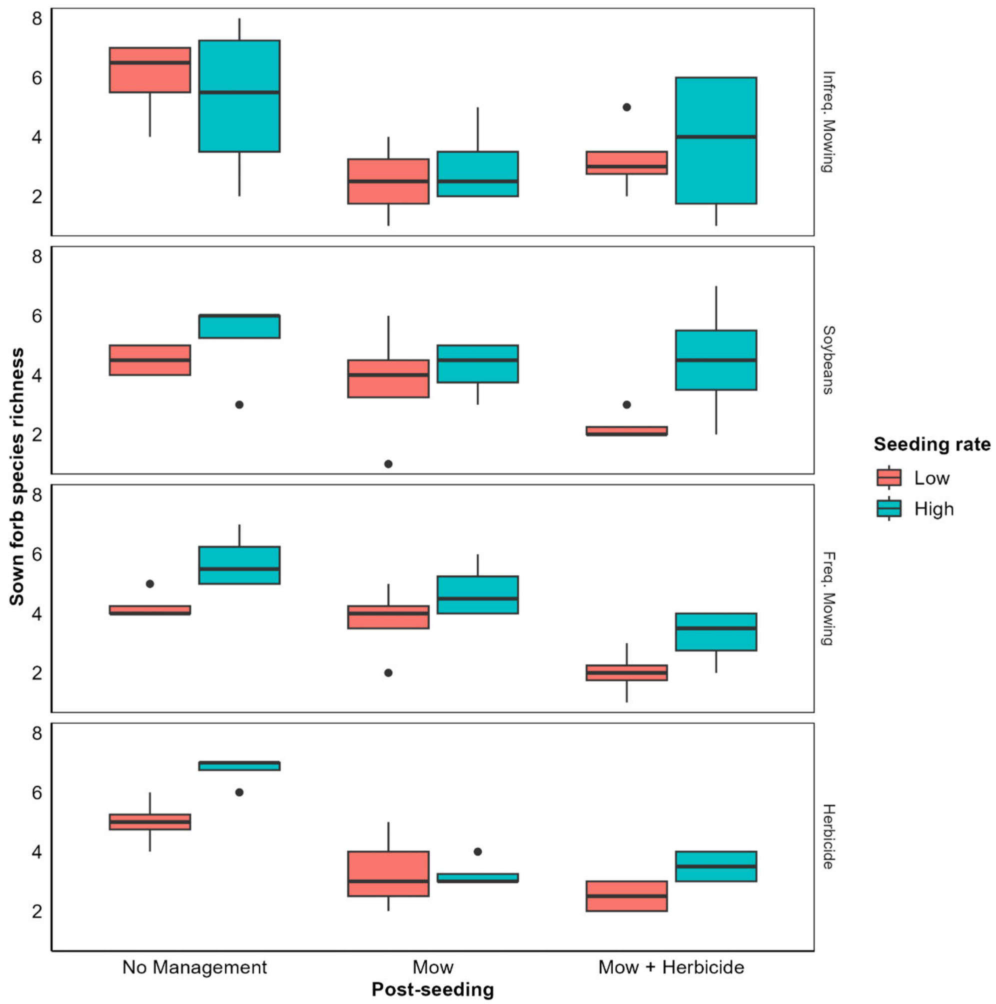

Figure 2. Total number of sown forb species (species richness) per quadrat in the final year of plant establishment (2020) across plots receiving each of the 24 treatment combinations.

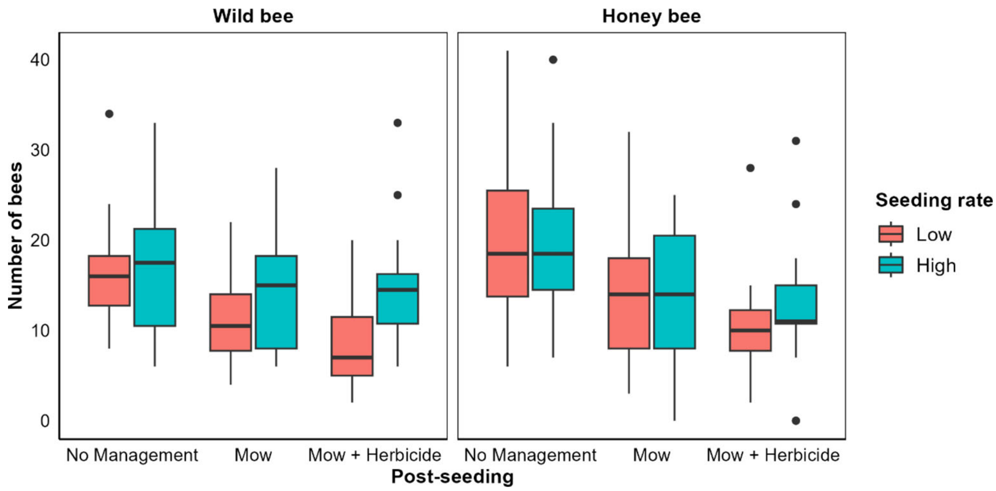

Figure 3. Average number of all wild bees (including bumble bees), or honey bees observed during the final year of plant establishment (2020) visiting plots with either high or low seeding rates, and one of the three post-seeding management strategies.

Post-seeding management significantly influenced wild bee visitation ($p = 0.003$), with the no management after seeding treatment resulting in a significantly higher number of wild bees observed than plots that received mow or mow + herbicide treatments ($p = 0.021$ and $p = 0.002$, respectively). The number of wild bees observed was also not significantly different between plots receiving these two treatments ($p = 0.359$). We found 24.3% more wild bees observed in plots receiving the high seeding rate compared to the low seeding rate ($p = 0.003$).

Discussion

Results from this study highlight how pre-seeding management and seeding rate significantly influence the establishment of native flower species when mown grassy areas are converted into habitat to support pollinators and other beneficial insects. Pre-seeding treatments influenced the initial plant establishment, but over time, this relationship became less apparent. After 3 years of establishment, the highest density of wildflowers was observed in plots that received either the pre-seeding herbicide or frequent mowing treatments, coupled with the high seeding rate. Similar studies have also found that reducing weed pressure through pre-seeding ground management is important for the initial germination and growth of sown native wildflowers (Hofmann & Isselstein 2004; Frances et al. 2010; Carvell et al. 2021). The herbicide and frequent mowing treatments were the most effective at removing weedy ground cover prior to seeding, which likely increased the initial germination and establishment of native plant species.

The high seeding rate had better overall establishment of the sown forbs than the low seeding rate, as expected with double the seed density. There were significantly higher stem counts, a higher percent ground cover of sown species, and a greater number of sown forb species present. While doubling the seeding rate did not result in a doubling of the flower densities, plots with the high seeding rate had the additional benefit of significantly lower ground cover by weedy forbs. Frances et al. (2010) also reported greater establishment of *Coreopsis lanceolata* in response to higher seeding rates, and recommendations in the literature often suggest higher seeding rates to ensure greater sown plant establishment (Aldrich 2002). Other studies have primarily focused on evaluating the species composition of seed mixes, rather than assessing the success of different overall seeding rates of identical seed mix ratios as our study did (Harmon-Threatt & Hendrix 2015; Drobney et al. 2020; Nichols et al. 2022). By directly comparing two seeding rates of the same wildflower mix, our findings highlight the importance of seed density for the establishment of new wildflower habitats.

Our comparison of post-seeding management strategies showed that the no management treatment had a greater ground cover and number of sown species established than either the mow or mow + herbicide treatments. This result is counter to previous studies where post-seeding mowing or frequent plant cutting accelerated or improved the establishment of native plants (Hofmann & Isselstein 2004; Meissen et al. 2020). It is possible that since our study plots were seeded in an area with mown grass with few naturalized invasive species, we limited the external pressures that may lead to increased weedy vegetation. Furthermore, the plots used in this study were smaller than a typical wildflower planting, and disturbances such as mowing may be more effective at improving wildflower establishment at more ecologically relevant scales (Gilgert & Vaughan 2011). In addition to the sown plant establishment being more successful in plots receiving no management post-seeding, we also found that the no management post-seeding treatments had the advantage of significantly reducing the ground cover of weeds, which is important for the long-term survival of wildflower habitats (Benvenuti & Bretzel 2017). Our results differ from the findings of Williams et al. (2007) in which frequent mowing promoted the establishment of forbs in warm-season prairie grass stand, leading to higher overall forb abundance after 10 years

(Williams et al. 2010). For this reason, we are hesitant to recommend the no management post-seeding management in all contexts and beyond a 3-year establishment period. Other studies have reported negligible or even negative consequences of intensive post-seeding management in wildflower plantings, which aligns more closely with our results (Norcini et al. 2023; Frances 2008; Angelella et al. 2019). Kirmer et al. (2018) found that the timing of post-seeding mowing influenced the success of that management; plots mowed once annually in June had significantly higher cover of sown target species compared to plots mowed annually in September, which had lower cover of sown target species and increased grass cover. This highlights the importance of strategic management timing with early summer mowing to prevent weed growth and seeding. Because our post-seeding mowing treatments were done monthly, it is possible that this was too frequent defoliation/cutting to benefit our target species, whereas Kirmer et al. (2018) found just one annual mowing in early summer (June) was beneficial to sown forb establishment. Mowing in the early summer could be adopted to reduce competition from weeds/grasses without excessively defoliating the sown forbs. Additionally, the costs involved in post-seeding management, including labor and equipment, should be considered by landowners when making management decisions. Given our results, greater investment should be made in pre-seeding management and increasing the seed density if the goal is to increase pollinator abundance and visitation. It should be noted, however, that our study had relatively low replication with only four plots receiving each of the 24 treatment combinations, so further investigation into these strategies in future studies with greater replication would be valuable for future decision-making. This was also a single-site study in a mid-western grass/weed dominated field with moderately eroded sandy loam soils, so future research should be conducted to determine how the efficacy of these various management strategies is influenced by environmental factors such as soil type, weed pressure, topography, and history of land use. Although this study was only done at one location, it is a good representation of potential areas where similar wildflower habitats are being established within the mid-western United States. Additionally, because all plots were at one location, this study is strengthened by the uniformity of environmental conditions that occurred across all treatment types, such as weather conditions and soil type, so the effects of those factor on plot success are negligible.

We focused on three main focal plant species, which are generally included in wildflower seed mixes to support pollinators in the Great Lakes region: *C. lanceolata*, *Monarda fistulosa*, and *Snovae-angliae novae-angliae*. These species have overlapping but staggered bloom periods, providing nutritional resources for bees throughout most of the Midwest region's growing season. Maintaining vegetation via mowing prior to seeding helped increase the initial establishment of *C. lanceolata*, however, this relationship declined temporally. This is expected because *C. lanceolata* is a short-lived perennial which can be outcompeted over time by weeds and other sown species (Grman et al. 2015). For *M. fistulosa* and *S. novae-angliae*, we found that once initially established, both species persist or increase in stem density over time. Considering the establishment of wildflower plantings depends on both the successful initial germination and growth of seedlings as well as their subsequent survival (Hofmann & Isselstein 2004), *M. fistulosa* and *S. novae-angliae* are excellent candidates for seed mixes developed for long-term pollinator conservation programs. Our study demonstrates that different management strategies may enhance initial seedling emergence for certain species, while ensuring long-term establishment over time for others. Additionally, the composition of established wildflower plantings does not always reflect the same proportions as the initial seed mixes, as some species may establish poorly while others may thrive, or volunteer native species may establish (Barr et al. 2016). As Scheper et al. (2021) recommends, the selection of flower species for seed mixtures should not only consider the target insect groups but also the establishment characteristics of the desired plant species.

Visits of bees to wildflower plots were most affected by post-seeding management, with the no management plots having the most honey bees visits during pollinator observations. However, because we did not collect flower species data during pollinator observations, it is possible that the higher abundance of honey bees observed in these plots may have been visiting the weedy species rather than the sown forbs. Minimizing disturbance post-seeding could benefit wild bees in other ways, as mowing may destroy some nesting structures (such as stems) and herbicide treatments applied to the soil could negatively affect soil nesting bees (Rondeau et al. 2022). We also found that the percent ground cover of sown forbs had the strongest positive correlation with total bee observations, so finding that bumble bees were least likely to be observed in plots receiving the highest level of post-seeding management (mow + herbicide) indicates that they were responding negatively to the lower plant density. This is similar to the findings of Carvell et al. (2021) who observed a significant positive effect of floral cover on solitary bee abundance, highlighting the importance of achieving effective establishment of dense wildflower plantings. Because our study plots were all within the same 0.4 ha field, we did not seek to measure differences in bee abundance or establishment across our management treatments, but rather to quantify the relative bee visitation and attractiveness to pollinators of each plot type.

Our results indicate that the higher seeding rate was beneficial for overall plant establishment during this 3-year study. According to Meissen et al. (2020), the costs of seeds for a reconstruction project can be 15 times greater than the costs of other management activities, such as frequent mowing or pre-seeding ground treatments. Due to the high cost of some native wildflower seeds mixes, it is important to conduct a cost–benefit analysis to determine if the advantages of high seeding rate and including particular species are worth the increased expense, and to identify the plant species that are lower cost per acre while also attracting diverse wild bee communities (M'Gonigle et al. 2016; Williams & Lonsdorf 2018). Since our results indicate that the high seeding rate resulted in a significant increase in seedling establishment, this initial investment could provide greater long-term value in terms of pollinators supported per dollar than the cost of mowing and herbicides. Our finding that no management during the post-seeding period resulted in higher establishment of sown species than other treatments, as well as greater sown forb cover, should encourage land managers to establish wildflower habitat since they can minimize continued post-seeding management while still reaping the desired outcomes and benefits of these plantings. Furthermore, less-intensively managed habitats have the potential to provide other critical non-flowering habitat components, such as nesting or overwintering sites for bees, other beneficial insects, birds, and other wildlife (Pywell et al. 2005; Carvell et al. 2021). When establishing wildflower habitat near crop land, farmers may be concerned about the potential risks the habitat might bring to their crops, such as increased weed or insect pest pressure (McCabe et al. 2017). Additional research on how these management strategies might impact pest or weed abundance on nearby farm merits future attention.

We found that pre-seeding management did not significantly affect the stem density of sown pollinator-attractive forbs, or the percent of ground covered by sown species. A doubling of the seeding rate translated into a significantly higher density of sown species, as well as an increased percent sown forb cover in the final year of the study. Seeding density also had the largest effect on wild bee observations, with high density seeding resulting in 24% higher bee observations in plots. Minimal post-seeding management resulted in higher stem density and a greater percent ground cover of sown forbs. Plots receiving no post-seeding management also had a significantly greater species richness compared to plots receiving intensive management. Our results suggest that investment in seeds will be more important than intensive post-seeding management for achieving abundant pollinator-supportive plantings in areas where existing grassy weed habitat is being converted into wildflower plantings to support pollinator communities.

ACKNOWLEDGMENTS

We thank the MSU Clarksville Research Center farm staff as well as H. Pointon, A. Veach, M. Sevener, S. Avendt, A. Peake, A. Jones, E. Espeland, and Y. Hodish for excellent technical assistance with plot maintenance and data collection. Thanks to L. Brudvig and E. Durnwald for advice on plot maintenance and sampling, and seed selection. This research was funded by the Operation Pollinator program and by AgBioResearch through support to R. I.

Data and code are provided at DOI: https://figshare.com/projects/Pollinator_planting_establishment_success_is_influenced_by_seeding_rate_and_pre-_and_post-seeding_management_strategies/179980.

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Supporting Information

The following information may be found in the online version of this article:

Table S1. Seed mix incorporating native flowering plants with diverse forb bloom times, and native grasses seeded in fall of 2017.
Table S2. Model selection for stem count per 0.5 m^2 in 2020 using AICc values.
Table S3. Deviance table for stem count per 0.5 m^2 in 2020.
Table S4. Model selection for ground cover of sown forbs using AICc values.
Table S5. Deviance table for main factors tested to determine their effects on percent ground cover of sown forbs.
Table S6. Model selection for percent ground cover of weed species using AICc values.
Table S7. Deviance table for percent ground cover of weed species.
Table S8. Model selection for sown forb species richness in 2020 using AICc values.
Table S9. Deviance table for sown forb species richness in 2020.
Figure S1. Graphical representation of study design to compare the relative effects of pre-treatment management, seeding rate, and post-seeding management treatments on wildflower establishment and pollinator responses.
Figure S2. Plot maps for pre-seeding treatments (A), seeding treatments (B), and post-seeding treatments (C).
Figure S3. Total stem counts over time of three focal wildflower species in plots receiving one of the four pre-seeding treatments (top) or three post-seeding treatments (bottom).
Figure S4. Average percent of ground covered by sown forbs (A) and weed species (B).
Figure S5. Average percent ground cover within whole plots of sown forbs species within each study year across plots receiving each of the 24 treatment combinations.
Figure S6. Relationships between observations of honey bees, bumble bees, and other wild bees.
Figure S7. Average number of all wild bees (including bumble bees), or honey bees observed visiting plots with each of the 24 treatment combinations.

Coordinating Editor: Justin Cao Luong

Received: 21 November, 2023; First decision: 18 January, 2024; Revised: 18 March, 2024; Accepted: 1 May, 2024