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Seed Mix Design and First-year Management Influences Ecological Outcomes in Prairie Reconstruction

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Seed Mix Design and First-year Management Influences Ecological Outcomes in Prairie Reconstruction

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Date	Dr. Justin C. Meissen, Member, Thesis Committee
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Abstract

Agricultural growth continues to diminish ecosystem services in the North American Corn Belt. To address these concerns, organizations, such as United States Department of Agriculture's Conservation Reserve Program (CRP), have initiated targeted conservation practices (CPs) to address specific challenges (e.g., CP2 to establish native grasses on highly-erodible lands and CP42 to establish pollinator habitat); however, these programs may be able to achieve greater impact with limited resources by attempting to balance multiple ecological benefits. To better understand factors that influence multifunctionality, we examined the effects of seed mix design and first year management (mowing) on ecological outcomes in a prairie reconstruction. Using experimental field trials, plots were established with three seed mixes, both with and without first-year mowing. The seed mixes differed in species diversity, grass-to-forb seeding ratios, and costs: the Economy mix had 21 species at a 3:1 grass-to-forb seeding ratio; the Pollinator mix had 38 species at a 1:3 grass-to-forb seeding ratio; and the Diversity mix had 71 species at a 1:1 grass-to-forb seeding ratio. The Economy and Pollinator mixes were designed to mimic commercially available seed mixes for CP21 and CP42 respectively, while the Diversity mix was customized to the mesic soil conditions at the site. To assess ecological outcomes, we measured native stem density, canopy cover, and inflorescence production over a four-year period (2015 – 2018). The Economy mix had high native plant cover and high grass stem density, but produced few inflorescences and had low floral diversity. The Pollinator mix had high inflorescence production and high floral diversity, but had high bare ground cover and weed abundance. In the Diversity mix, native cover and grass stem density were comparable to the Economy mix, while inflorescence production and floral diversity were comparable to the Pollinator mix. Our results suggest that a well-designed seed mix, customized to site conditions, can effectively address multiple conservation concerns in a prairie reconstruction.

Acknowledgments

I would like to thank my research advisor Mark Sherrard and advisory committee members Justin Meissen and Kenneth Elgersma for their assistance with this research project and thesis. I would also like to thank Esther Edgerton and Kylie Bundt for assistance in the field. This research was supported by The Iowa Nutrient Reduction Center (Grant #: 2016-07).

This thesis represents the culmination of four years of data collection on this research project. The study was originally designed by Dave Williams of the Tallgrass Prairie Center. Williams collected the first year (2015) of data on the project. Justin Meissen was the lead researcher on the project in years two – four (2016 – 2018). My roles in this research project include: participating in data collection during year four (2018), data analysis, graph preparation, and thesis writing. For brevity, and to maintain active voice, I use the term “we/us” throughout the thesis, even when describing methods for which I was not directly involved.

List of Figures

Fig. 1: Site Map ……………………………………………………………..……7

Fig. 2: Species richness and stem density …………………………………………… 11

Fig. 3: Canopy cover ..……………………………………………………………… 14

Fig. 4: Cumulative inflorescence production (2016 – 2018)…………………………… 17

Fig. 5: Floral richness and evenness..…………………………………………..…. 18

Fig. 6: Cost-effectiveness ………………………………………………………...20

List of Tables

Table 1: Repeated Measures ANOVA: Species richness and stem density ..……..…… 10

Table 2: Repeated Measures ANOVA: Canopy cover …..…………………………..…… 13

Table 3: Two-way ANOVA: Cumulative inflorescence production (2016-2018) ...….. 16

Table 4: Two-way ANOVA: Cost-effectiveness …….……………………..….… 19

Appendices

Appendix A: Species list and seeding rates of the Economy Mix ………………….…. 29

Appendix B: Species list and seeding rates of the Pollinator Mix …………………..… 30

Appendix C: Species list and seeding rates of the Diversity Mix ………………….…. 32

Appendix D: Inflorescence production by year ……………………………………….. 35

Introduction

Land use intensification and rising production inputs continue to diminish ecosystem services in the North American Corn Belt. Reduced pollinator abundance (Cameron et al. 2011), deteriorating water quality (Jones et al. 2018), and soil erosion (Wright & Wimberly 2013) have all become large-scale stressors facing ecosystems in these agricultural landscapes. In response, organizations have initiated targeted programs to address specific conservation challenges. For example, the United States Department of Agriculture (USDA) has created conservation initiatives to enhance single ecosystem services, such as the upland game bird provision (CP33, Habitat Buffers for Upland Birds), highly erodible land conservation (CP2, Establishment of Permanent Native Grasses), and flood control (CP23, Wetland Restoration) (USDA 2018a). An especially popular conservation initiative in recent years has been the restoration of pollinator habitat (CP42). Approximately 160,000 ha in Corn Belt states have been dedicated to pollinator habitat plantings (USDA 2018b). Recently, congress has proposed major cuts to CRP funding and national enrollment caps. This suggests that future conservation programs may need to be executed in a manner that is both ecologically effective and cost-effective. Conservation programs may be able to achieve greater impact with limited resources (i.e., be more cost-effective) by attempting to balance multiple ecological benefits.

Previous research has shown that diverse ecosystems provide a wide variety of ecological benefits simultaneously (MacFayden et al. 2012; Wratten et al. 2012). For example, biodiversity-ecosystem function studies suggest that high diversity systems tend to have higher productivity, higher rates of nutrient cycling and capture, higher rates of decomposition, and greater stability of ecosystem services than low diversity systems (Cardinale et al. 2012). In the Midwestern United States specifically, species-rich tallgrass prairies provide several ecosystem services when restored on the landscape (Asbjornsen et al. 2014; Schulte et al. 2017). For example, strategically restoring prairie on 10% of agricultural fields can reduce N and P losses by up to 82% (Zhou et al. 2014). Further, integrating prairie into agricultural fields and other parts of the rural landscape can reduce sediment runoff (Helmers et al. 2012), increase pollinator abundance (Ries et al. 2001; Schulte et al. 2017), and increase bird species richness (Schulte et al. 2017). While the multiple ecological benefits of tallgrass prairie are well known, no studies have investigated how to produce the maximum ecological benefit per unit project cost (i.e., how to maximize cost-effectiveness in prairie reconstruction).

Seed mix design is the biggest determinant of project costs and ecological outcomes in prairie reconstruction (Larson et al. 2011, 2017; Grman et al. 2013; Phillips-Mao et al. 2015). One aspect of seed mix design that is particularly influential for both costs and outcomes is the grass-to-forb seeding ratio. From a cost perspective, seed mixes with a high grass-to-forb ratio are less expensive than seed mixes with a low grass-to-forb ratio because grass seed is generally less expensive than forb seed (e.g., Prairie Moon Nursery 2012). However, designing mixes in which the seeding rate of one functional group is either too high or too low can adversely affect specific ecosystem services. For example, seed mixes in which the grass seeding rate is too high can produce grass-dominated stands where forbs establish poorly and do not persist (Dickson & Busby 2009; McCain et al. 2010; Török et al. 2010; Valko et al. 2016); these stands would have little value as pollinator habitat (Hopwood 2008). Conversely, seed mixes in which the grass seeding rate is too low can produce stands with low cover (i.e., a high amount of bare ground); these stands would be more susceptible to weed invasion and provide less protection against soil erosion and water quality degradation (Burke et al. 1996). Another aspect of seed mix design that influences costs and outcomes is species selection. A customized seed mix, in which species moisture tolerances are matched to site soil conditions, should produce stands that establish readily and persist long-term (Smith et al. 2010). Many reconstruction projects simply use “off-the-shelf” seed mixes designed to achieve specific program goals (e.g., prioritizing short grasses for CP42 pollinator habitat to reduce competition for forbs; USDA 2011). If a seed mix contains species that perform poorly under local site conditions, it will reduce the cost-effectiveness of the reconstruction.

First-year management can also influence the costs and outcomes of prairie reconstruction. Fast-growing annual weeds are a common problem in prairie reconstruction. In post-agricultural sites where many reconstructions occur, these weeds quickly establish and become dominant before the prairie seeds germinate (Smith et al. 2010). The resulting low-light, competitive conditions are not well suited to slow-growing prairie seedlings that require multiple growing seasons to reach maturity. Previous research suggests that mowing can promote prairie plant establishment by increasing light availability to developing seedlings. For example, Williams and others (2007) found that frequent mowing promotes the establishment and persistence of forbs sown into warm-season grass stands. The impact of this management was long lasting as forb abundance remained higher in mowed plots than in control plots 10 years after the forbs were sown (Williams et al. 2010). Other research has shown that mowing maintains diversity (Collins et al. 1998) and reduces invasion (Smith et al. 2018) in grassland systems. Because the seed costs of a reconstruction project can be 15 times greater than the cost of establishment mowing (Phillips-Mao et al. 2015), a significant increase in seedling survival would represent a large increase in cost-effectiveness.

In this study, we investigate the impacts of seed mix design and first-year establishment mowing in experimental field trials. We established research plots with three different seed mixes, both with and without first-year mowing. The seed mixes differed in diversity, grass-to-forb seeding ratio, degree of soil type customization, and cost. We compared species richness, stem density (native grasses and forbs), canopy cover (native plants, annual weeds, perennial weeds, and bare ground), inflorescence production, and floral richness between treatment combinations.

Methods

Study Site

This study was conducted at the Iowa State University Northeast Research and Demonstration Farm near Nashua, Iowa (42°56’ N, 92°34’ W). The site is level with slopes not exceeding a 5% grade. Soil composition is primarily poorly drained Clyde clay loams with a minor component of somewhat poorly drained Floyd loams (NRCS 2016). The land was used for corn and soybean production, prior to site establishment in 2015.

To prepare the research area, the site was seeded with soybeans the year prior to research plot establishment. A pre-emergent herbicide (Zidua®, BASF Corporation, Research Triangle, NC) was applied in May 2014 at a rate of 210 g ha^{-1} and a post-emergent herbicide (Roundup WeatherMAX, Monsanto Company, St. Louis, MO) was applied in mid-July at an unknown application rate. To create a suitable seedbed, the site was chisel plowed in March 2015 and field cultivated twice in April 2015. The prepared seedbed was loose, with clods less than 6.4 mm in diameter. To stabilize the soil as prairie seedlings established, a nurse crop of oats was planted at a rate of 36.3 kg ha^{-1}.

Seed Mixes

We established plots with three different seed mixes. Seed mixes differed in their grass-to-forb seeding ratio and degree of soil type customization. The Economy mix was designed to resemble a seed mix that met the specifications for USDA's Grass Filter Strip Conservation Practice (CP21). It included 21 species at a 3:1 grass-to-forb seeding ratio (Appendix A). The Pollinator mix was designed to resemble a seed mix that met the specifications for USDA's Pollinator Habitat Conservation Practice (CP42). It included 38 species at a 1:3 grass-to-forb seeding ratio (Appendix B). The Diversity mix included 71 species at a 1:1 grass-to-forb seeding ratio (Appendix C) and was designed to resemble a remnant prairie of matching geographic and soil conditions on site. The costs of the Economy, Pollinator, and Diversity mixes were $321, $909, and $719 per hectare respectively.

We purchased seed from native seed nurseries in Iowa and adjacent states in January 2015. Seeds were stored at 4°C and 45% RH prior to planting. To ensure accuracy in seeding rates and seed purity, we calculated seeding rates for each species using pure live seed (PLS). We standardized the overall seeding rate of each mix to approximately 430 PLS m^{-2}. We weighed, bagged, and mixed the seed for each plot separately.

Experimental Design

We established 36 research plots using a split-plot design with two spatial blocks. Eighteen research plots (6.1 m × 8.53 m each) were established in each of two blocks (12.2 m × 77.11 m each). Within each block, three replicate plots of each seed mix were randomly established in 12.2 m × 8.53 m strips and the mowing treatment was applied to one randomly-selected half of each 12.2 m × 8.53 m strip. This resulted in an overall design of 3 seed mixes × 2 mowing treatments × 3 replicates × 2 blocks = 36 research plots (Fig. 1). Because of minor flooding during establishment, plot 18 (SE corner of block 2, Fig. 1) was excluded from all analyses.

We drill-seeded the research plots in April 2015. Drilling was unidirectional to eliminate seed contamination between adjacent plots. Each plot was seeded independently using a Truax FLX-86U no-till drill (Truax Company, Inc., New Hope, MN) with a John Deere JD-5325 tractor. To minimize contamination between seed mixes, we cleaned out the drill between each seeding.

First-year Management

We applied a first-year (2015) mowing treatment to half of the plots of each seed mix. Mowing was performed when the vegetation height exceeded 50 cm and the vegetation was cut to a height of 11.4 cm. We mowed the plots four times in 2015 (June 16, July 23, August 13, November 4) and all remaining thatch was left on site. Mowing was not performed in 2016, 2017, or 2018.

Data Collection

In each year of the study (2015-2018), we measured stem density during the month of September. Stem density was assessed in five-0.1 m^2 quadrats in each plot. Quadrats were placed at 1 m intervals along a 5 m transect that was established at a random position within each plot. To minimize edge effects, quadrats were not placed within 1 m of any plot edge. In each quadrat, we identified and counted all stems (ramets)

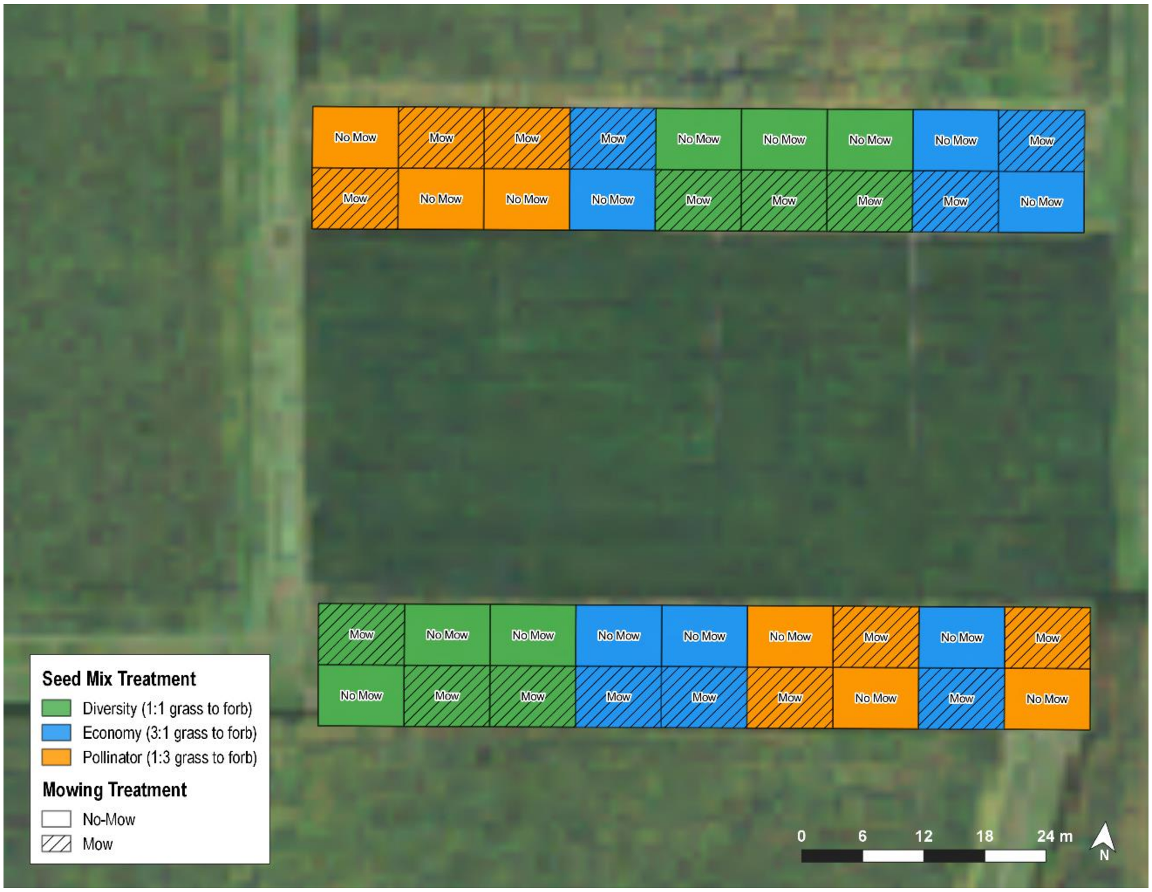

Figure 1. Experimental layout at the Iowa State University Northeast Research and Demonstration Farm near Nashua, Iowa (Image credit: Justin Meissen).

>10 cm of each species. During this survey, we also recorded native species richness as the total number of native species present within each plot.

In the same quadrats used to assess stem density, we measured canopy cover of annual weeds, perennial weeds, native plants, and bare ground. We also recorded the number of inflorescences of species rooted in the quadrat. Cover and inflorescence number were measured over a three-year period (from 2016-2018). We report inflorescence number as cumulative inflorescence production over the three year period (2016-2018).

We assessed the cost-effectiveness of each seed mix × mowing treatment combination in three ways: the cost per 1K native stems, the cost per 1K forb stems, and the cost for 1K native inflorescences. Cost-effectiveness was calculated as: the cost of the seed mixture (per plot) divided by the variable of interest (i.e., the number of 1K native stems in 2018, the number of 1K native forb stems in 2018, or the number of 1K inflorescences produced between 2016 and 2018) per plot.

Data Analysis

We analyzed stem density, species richness, and canopy cover using repeated measures ANOVA, with seed mix and mowing as fixed factors, year as the repeated measure, and plot nested within block as a random factor. To meet the assumptions of normality and homoscedasticity of residual variance, grass stem density, forb stem density, and cover of annual weeds were cube-root transformed, cover of bare ground was square root transformed, and perennial weed cover was log(y+0.1)-transformed. Cumulative inflorescence number (2016-2018) and cost-effectiveness were analyzed using two-way ANOVA with seed mix and mowing as fixed factors and plot nested within block as a random factor. Within year post-hoc comparisons of significant treatment effects were made using one-way ANOVA and Tukey HSD tests. All data were analyzed in R (v. 3.2.3, R Core Team 2013).

Results

Species Richness

Species richness differed between seed mixes (Table 1). The Diversity mix had higher species richness than the Pollinator and Economy mixes in all four years of the study and the Pollinator mix had higher species richness than the Economy mix in 2015 and 2017 (Fig. 2A). First year management (mowing) influenced species richness, but this effect was not consistent across study years (Table 1). Species richness was higher in mowed plots than in plots that were not mowed in 2015 and 2016, but not in 2017 and 2018 (Fig. 2B). Species richness changed with time (Table 1) and was generally lower in earlier years (2015 and 2016) than later years (2017 and 2018) (Fig. 2A,B).

Stem Density

Native forb and grass stem density differed between seed mixes (Table 1). In most years, forb stem density was higher in the Diversity and Pollinator mixes than in the Economy mix (Fig. 2C; forb stem density did not differ significantly between Diversity and Economy mixes in 2016), while grass stem density was higher in the Economy and

Diversity mixes than in the Pollinator mix (Fig. 2E). In general, grass and forb stem density were higher in mowed plots than in plots

Table 1. Repeated measures ANOVA comparing inflorescence number, species richness, grass stem density, and forb stem density between treatment combinations. ‘Between’ represents variation between factors (the mowing and seed mix treatments) and ‘Within’ represents variation within factors across the repeated measure (year). Reported values are: numerator and denominator degrees of freedom (*df*), F-statistics (*F*), and P-values (*P*). Significant terms (p<0.05) are indicated in bold.

	Species richness			Grass stems (m^{-}2)			Forb stems (m^{-2})		
	df	*F*	*P*	*df*	*F*	*P*	*df*	*F*	*P*
Between									
Mow	1, 62	**11.242**	**0.001**	1, 62	**42.335**	**0.000**	1, 62	2.759	0.102
Seed Mix (SM)	2, 13	**28.047**	**0.000**	2, 13	**53.871**	**0.000**	2, 13	**27.427**	**0.000**
Mow × SM	2, 62	0.067	0.936	2, 62	0.194	0.824	2, 62	**4.469**	**0.015**
Within									
Year (Y)	1, 48	**42.833**	**0.000**	1, 48	**91.388**	**0.000**	1, 48	**139.973**	**0.000**
Mow × Y	1, 62	**14.808**	**0.000**	1, 62	3.298	0.074	1, 62	2.487	0.120
SM × Y	2, 48	1.054	0.357	2, 48	2.316	0.110	2, 48	0.544	0.584
Mow × SM × Y	2, 62	0.907	0.409	2, 62	1.479	0.236	2, 62	1.337	0.270

Inflorescences: square-root transformed

Grass stems and Forb stems: cube-root transformed

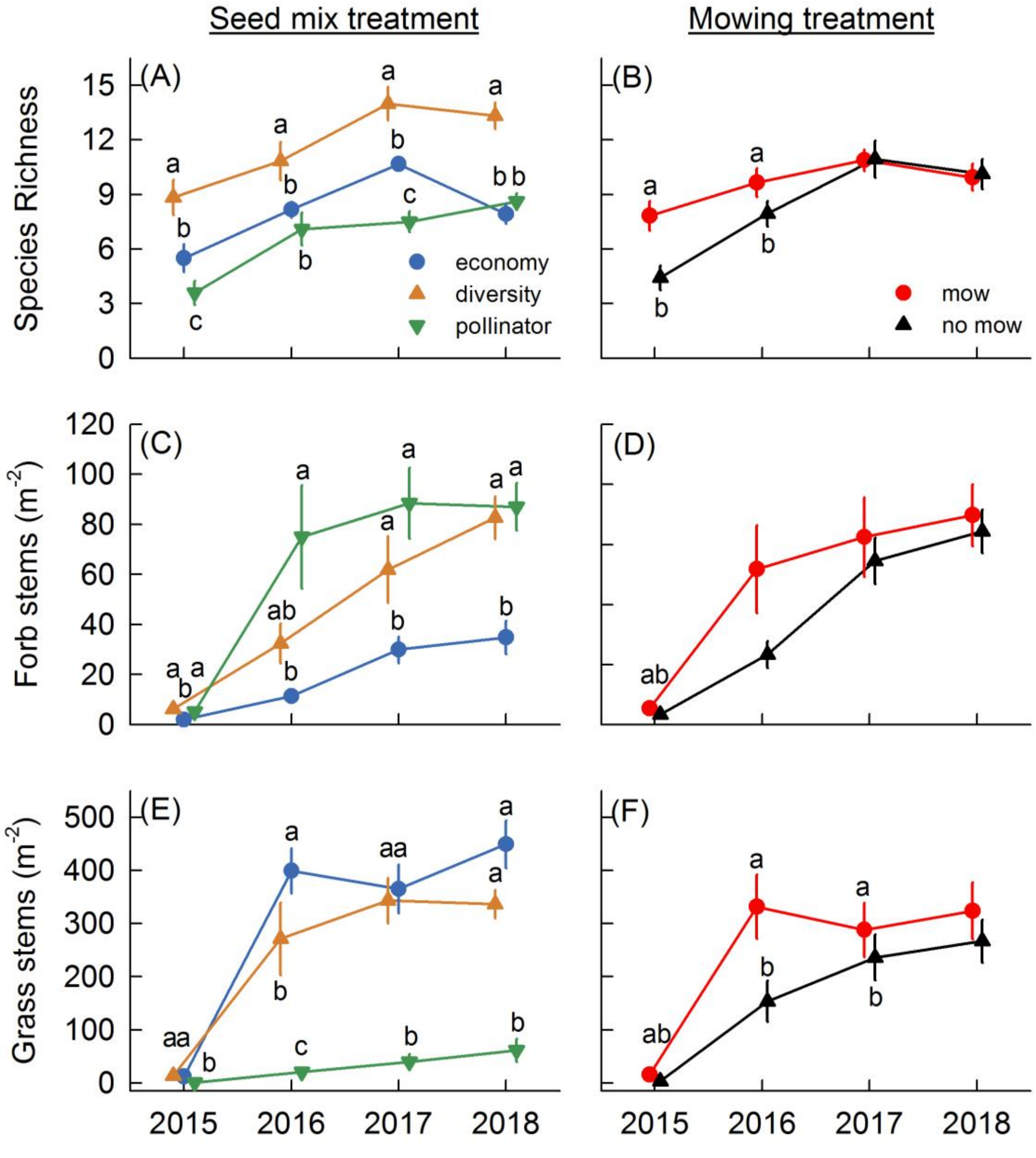

Figure 2. Differences in species richness, forb stem density, and grass stem density between seed mixes and mowing treatments. Values presented are annual averages (± 1 SE). Significant differences between seed mixes and mowing treatments (within a given year) based on Tukey's post hoc tests are indicated with different letters.

that were not mowed (Table 1; Fig. 2D,F). Forb and grass stem density changed with time (Table 1) and were generally lower in earlier years (2015 and 2016) than in later years (2017 and 2018; Fig. 2A,B).

Canopy Cover

Canopy cover of native plants, annual weeds, perennial weeds, and bare ground differed between seed mixes (Table 2; term for perennial weeds marginally significant, *p*=0.096). Native plant cover was higher in the Economy and Diversity mixes than in the Pollinator mix in most study years (Fig. 3A; native cover did not differ significantly between Diversity and Pollinator mixes in 2016), annual weed cover was higher in the Pollinator mix than in the Economy and Diversity mixes in 2017 (Fig. 3C), perennial weed cover was higher in the Pollinator mix than in the Economy and Diversity mixes in 2017 and 2018 (Fig. 3E), and bare ground cover was higher in the Pollinator mix than in the Economy and Diversity mixes every year (Fig. 3G). Mowing had a significant impact on the cover of native plants and annual weeds, but this effect was not consistent across years (Table 2). Specifically, native plant cover was higher and annual weed cover was lower in mowed plots than in plots that were not mowed in 2016, but this effect was no longer significant in 2017 and 2018 (Fig. 3B,D). Canopy cover changed with planting age (Table 2). In general, native plant and perennial weed cover increased with planting age, while annual weed and bare ground cover decreased with planting age (Fig. 3A,C,E,G).

Table 2. Repeated measures ANOVA comparing the cover of native plants, annuals weeds, perennial weeds, and bare ground between treatment combinations. 'Between' represents variation between factors (the mowing and seed mix treatments) and 'Within' represents variation within factors across the repeated measure (year). Reported values are: numerator and denominator degrees of freedom (*df*), F-statistics (*F*), and P-values (*P*). Significant terms ($p<0.05$) are indicated in bold.

	Native plants			Annual weeds			Perennial weeds			Bare ground		
	df	*F*	*P*	*df*	*F*	*P*	*df*	*F*	*P*	*df*	*F*	*P*
Between												
Mow	1, 45	**27.832**	**0.000**	1, 45	**31.432**	**0.000**	1, 45	0.001	0.972	1, 45	2.427	0.126
Seed Mix (SM)	2, 13	**22.544**	**0.000**	2, 13	**9.506**	**0.003**	2, 13	2.823	0.096	2, 13	**29.688**	**0.000**
Mow × SM	2, 45	0.253	0.778	2, 45	0.508	0.605	2, 45	0.788	0.461	2, 45	1.820	0.174
Within												
Year (Y)	1, 31	**81.889**	**0.000**	1, 31	**49.327**	**0.000**	1, 31	**75.244**	**0.000**	1, 31	**23.979**	**0.000**
Mow × Y	1, 45	**24.603**	**0.000**	1, 45	**9.560**	**0.003**	1, 45	0.429	0.516	1, 45	3.957	0.053
SM × Y	2, 31	**5.221**	**0.011**	2, 31	0.021	0.979	2, 31	3.712	0.036	2, 31	2.907	0.070
Mow × SM × Y	2, 45	1.481	0.238	2, 45	2.691	0.079	2, 45	0.144	0.867	2, 45	1.752	0.185

Annual weed cover: cube-root transformed

Bare ground cover: square root transformed

Perennial weed: log(y+0.1) transformed

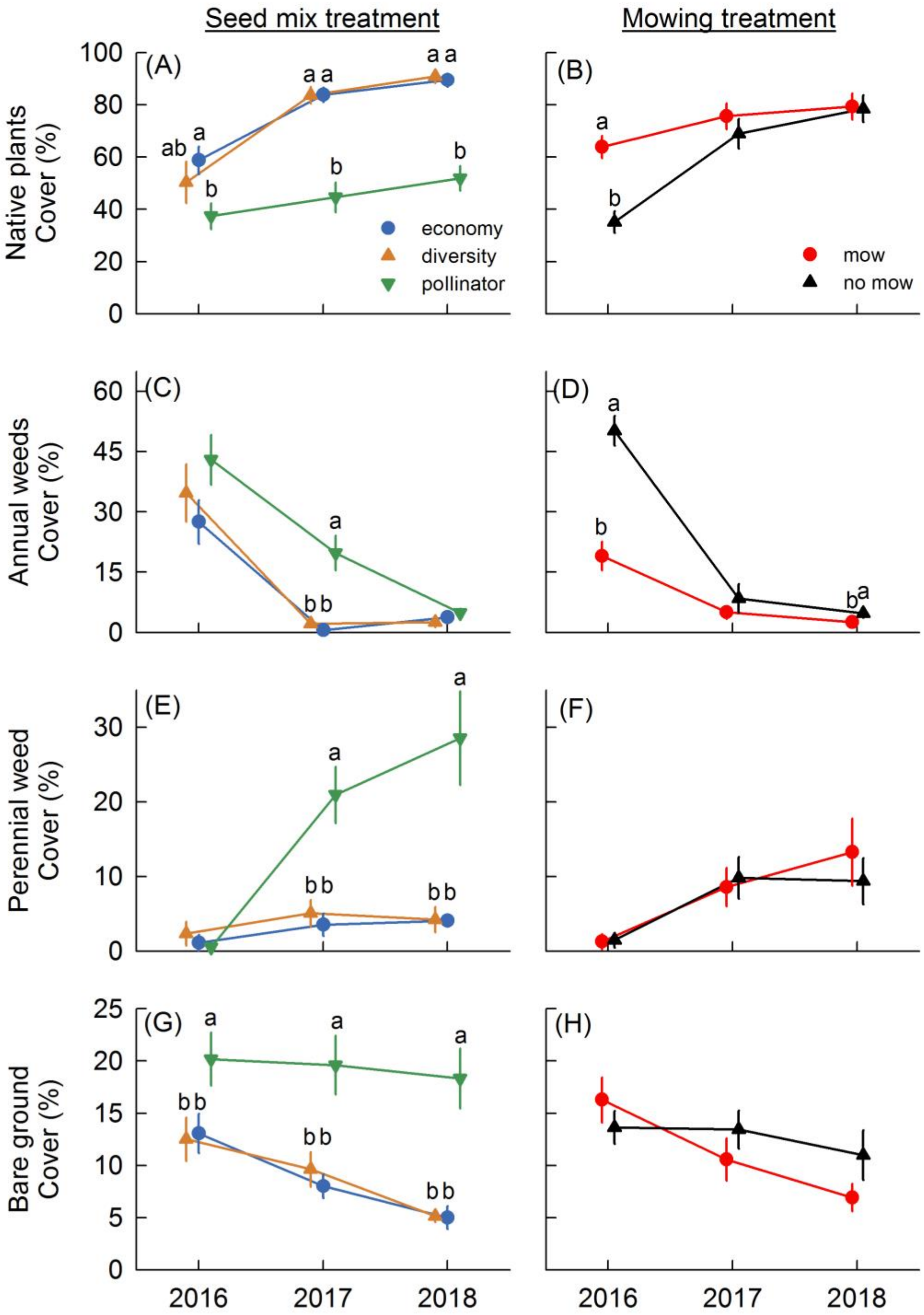

Figure 3. Differences in canopy cover between seed mixes and mowing treatments. Values presented are annual averages (± 1 SE). Significant differences between seed mixes and mowing treatments (within a given year) based on Tukey's post hoc tests are indicated with different letters.

Cumulative Inflorescence Production (2016 – 2018)

The total number of inflorescences produced during the study period (excluding the first year-establishment period) differed between seed mixes (significant seed mix term, Table 3). The Pollinator mix produced more inflorescences than the Diversity mix and the Diversity mix produced more inflorescences than the Economy mix (Fig. 4). In the Diversity and Pollinator mixes, inflorescence production was higher in mowed plots than in plots that were not mowed; conversely, in the Economy mix, fewer inflorescences were produced in mowed plots than in plots that were not mowed (significant mow × seed mix term, Table 3; Fig. 4). In total, seven forb species flowered in the Economy mix, 16 forb species flowered in the Diversity mix, and 13 forb species flowered in the Pollinator mix across mowing treatments (Fig. 5).

Cost-effectiveness

Cost per 1K native stems and cost per 1K native forb stems differed between seed mixes (significant seed mix term, Table 4). In general, cost per 1K native stems and cost per 1K native forbs was lowest in the Economy mix and highest in the Pollinator mix (Fig. 6). The effect of seed mix design on cost per 1K inflorescences differed between mowing treatments (significant mow × seed mix term, Table 4). In mowed plots, the cost per 1K inflorescences was lower in the Diversity and Pollinator mixes than in the Economy mix, but in plots that were not mowed, the cost per 1K inflorescences was lower in the Economy and Pollinator mixes than in the Diversity mix (Fig. 6).

Table 3. Two-way ANOVA comparing cumulative inflorescence number (2016 – 2018) between treatment combinations. The mowing and seed mix treatments were fixed effects in the model. Reported values are: numerator and denominator degrees of freedom (*df*), F-statistics (*F*), and P-values (*P*). Significant terms (p<0.05) are indicated in bold.

	df	*F*	*p*
Mow	1, 14	**6.547**	**0.023**
Seed Mix (SM)	2, 13	**10.411**	**0.002**
Mow × SM	2, 14	**6.662**	**0.009**

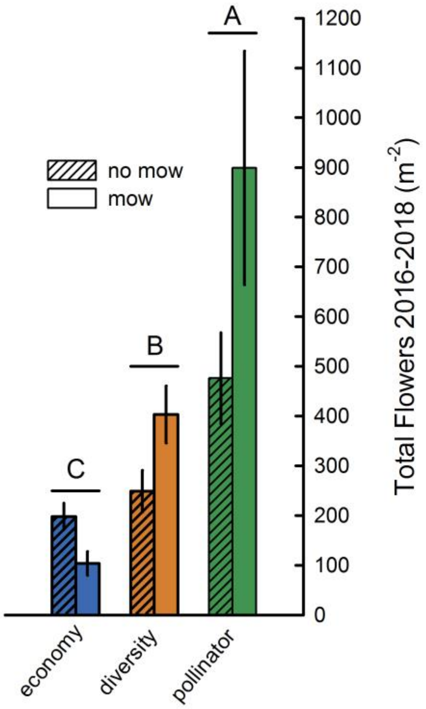

Figure 4. Differences in cumulative inflorescence production (2016-2018) between seed mixes and mowing treatments. Values presented are average cumulative inflorescence production (± 1 SE). Significant differences between seed mixes based on Tukey's post hoc tests indicated with different letters.

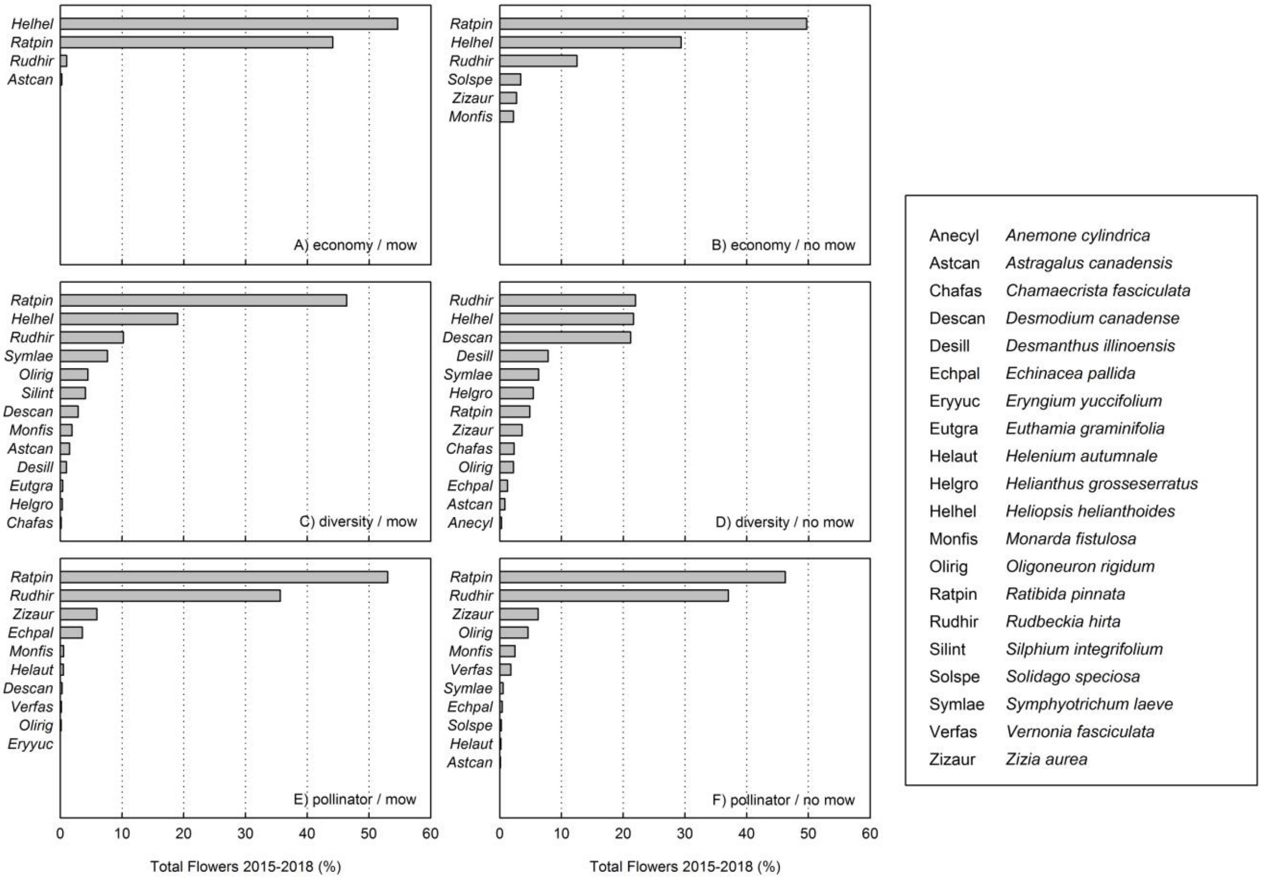

Figure 5. Differences in floral richness and evenness between seed mixes and mowing treatments. Values represent percent of cumulative inflorescence production for each species within a given treatment combination. Species abbreviations are:

Table 4. Two-way ANOVA comparing cumulative cost-effectiveness between treatment combinations. Cost-effectiveness was determined as: the cost of the seed mixture per plot divided by the variable of interest (i.e., the number of 1K native stems (in 2018), the

number of 1K native forb stems (in 2018), or the number of 1k inflorescences produced between 2016 and 2018) per plot. The mowing [Mow] and seed mix treatments were fixed effects in the model. Reported values are: numerator and denominator degrees of freedom (*df*), F-statistics (*F*), and P-values (*P*). Significant terms are indicated in bold.

	Cost / 1K Native stems			Cost / 1K native forb stems			Cost / 1K native inflorescences		
	df	*F*	*P*	*df*	*F*	*P*	*df*	*F*	*P*
Mow	1, 14	0.037	0.850	1, 14	0.170	0.686	1, 14	0.005	0.945
Seed Mix (SM)	2, 13	**78.949**	**0.000**	2, 13	**28.394**	**0.000**	2, 13	2.706	0.104
Mow × SM	2, 14	2.308	0.136	2, 14	0.439	0.653	2, 14	**15.210**	**0.000**

Cost / 1K native stems: 1/sqrt-transformed

Cost / 1K native forb stems: sqrt-transformed

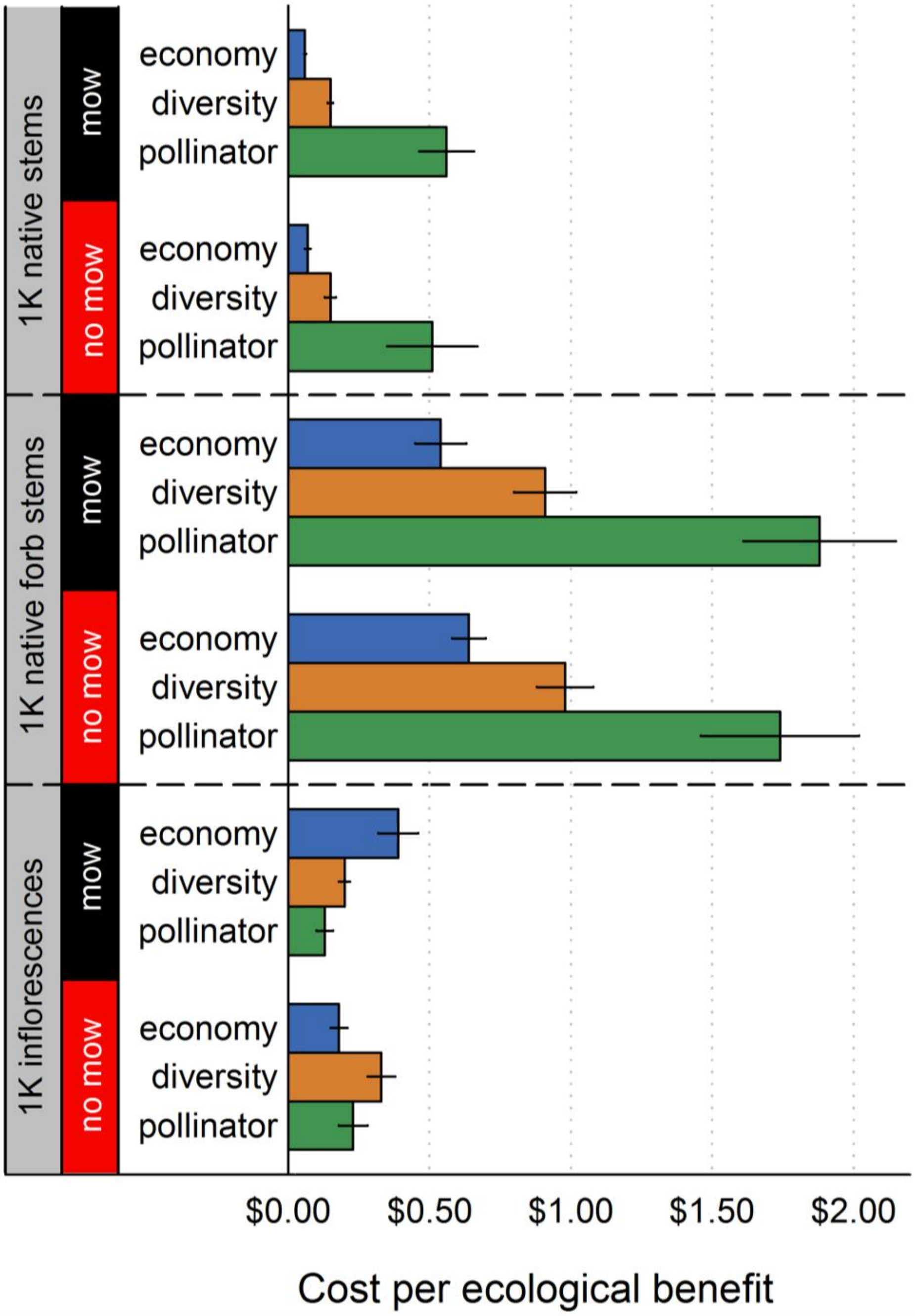

Figure 6. Differences in cost-effectiveness between seed mixes (within a given mowing treatment). Cost-effectiveness was calculated as: the cost of the seed mixture (per plot) divided by one of the following: the number of 1K native stems in 2018; the number of 1K native forb stems in 2018; or, the number of 1K inflorescences produced between 2016 and 2018, per plot.

Discussion

Consistent with previous studies (Larson et al. 2011, 2017; Grman et al. 2013; Phillips-Mao et al. 2015), we found that seed mix design was a significant determinant of ecological outcomes in prairie reconstruction. The grass-to-forb seeding ratio of our three seed mixes had a pronounced effect on native stem density and cover, which are key determinants of erosion control (Boyd 1942; Ellison et al. 1950; Durán Zuazo & Rodríguez Pleguezuelo 2008) and weed resistance (Schramm 1992; Bergelson et al. 1993; Stevenson et al., 1995; van der Putten et al. 2000; Warren et al., 2002; Lepš et al., 2007; Török et al. 2010; Valko et al. 2016). The grass-to-forb seeding ratio also influenced inflorescence production, which is a key determinant pollinator habitat value (Hopwood 2008; Pywell et al. 2011). We also found that mowing influences ecological outcomes in prairie reconstruction. Mowing accelerated forb establishment and inflorescence production which would increase the lifetime value of a prairie reconstruction as pollinator habitat. While several studies have considered the influence of seed mix design and management on species establishment and ecosystem services in prairie reconstructions (e.g., Maron & Jefferies 2001; Antonsen and Olsson 2005; Grman et al. 2013; Larson et al. 2011, 2017), our study demonstrates that seed mix design and mowing influence the ability to simultaneously provide erosion control and pollinator services (i.e., multifunctionality) in prairie reconstruction.

Our results suggest that the Economy mix provides high erosion control, high nutrient retention, and high weed resistance, but few resources for pollinators. The Economy mix was designed to resemble a seed mix that met the specifications for USDA’s Grass Filter Strip Conservation Practice (CP21). The primary goals of this practice are to intercept and filter nutrients from agricultural runoff and reduce soil erosion (USDA 2015). Prairie grasses are well suited to these goals because they have high root length density and tend to fill canopy gaps (Boyd 1942; Ellison et al. 1950; Durán Zuazo & Rodríguez Pleguezuelo 2008). Indeed, we found that the Economy mix had high grass stem density, high native plant cover, low weed abundance, and little bare ground. Because this mix was the least expensive (\$321 ha^{-1}) it achieved several ecological benefits in a cost-effective manner. It was the most cost-effective seed mix for producing native stems and native forb stems. Although the Economy mix also produced inflorescences in a cost-effectiveness manner, this result likely overstates the value of this mix for pollinators. The Economy mix produced the fewest inflorescences and had lowest floral richness of the three mixes. Approximately 80% of all inflorescences were produced by two species (*Ratibida pinnata* and *Heliopsis helianthoides*). Overall, the Economy mix achieved the primary goals of CP21 but had poor multifunctionality.

Our results suggest that the Pollinator mix provides high quality pollinator habitat, but low erosion control, low nutrient retention, and little resistance to weed invasion. Previous research has shown that high-diversity wildflower mixes promote stable vegetative communities and support higher pollinator richness than low-diversity mixes (Pywell et al. 2011). The Pollinator mix was designed to resemble a seed mix that met the specifications for USDA's Pollinator Habitat Conservation Practice (CP42), the goals of which are to establish habitat with a minimum of nine pollinator-friendly species blooming throughout the growing season. In an effort to reduce competition for forbs (Dickson & Busby 2009; McCain et al. 2010; Török et al. 2010; Valko et al. 2016), CP42 seed mixes are designed with a low grass-to-forb seeding ratio (1:3). Consistent with these goals, the Pollinator mix had high forb stem density, high inflorescence production, and high floral richness. However, previous studies have also shown that seed mixes in which the grass-to-forb seeding ratio is too low result in more bare ground (e.g., Dickson & Busby 2009), making them more prone to soil erosion (Ellison 1950) and weed invasion (Schramm 1990). These are major concerns in many CRP sites (Jeklinski & Kulakow 1996). Indeed, the Pollinator mix also had low grass stem density, high weed cover, and high bare ground cover. From a cost-effectiveness perspective, the Pollinator mix produced inflorescences in a cost-effective manner, but was the least cost-effective seed mix for producing native stems and native forb stems. Overall, the Pollinator mix achieved the primary goals of CP42 but had poor multifunctionality.

Our results suggest that the Diversity mix, provides high erosion control, high nutrient retention, high weed resistance, and high quality pollinator habitat. The Diversity mix included 71 species at a 1:1 grass-to-forb seeding ratio and was designed to resemble a remnant prairie of matching geographic and soil conditions on site. Similar to the Economy mix, the Diversity mix had high grass stem density, high native plant cover, low weed abundance, and little bare ground. Similar to the Pollinator mix, the Diversity mix had high forb stem density, high inflorescence production and high floral richness. The Diversity mix also provided these ecological benefits in a cost-effective manner. In spite of its lower forb seeding ratio, the Diversity mix produced inflorescences with comparable cost-effectiveness to the Pollinator mix; it also had comparable floral richness. In spite of its higher cost, the Diversity mix produced native stems with comparable cost-effectiveness to the Economy mix. Overall, our results suggest that with careful consideration of seed mix design it is possible to achieve multifunctionality in prairie reconstruction, which could ultimately improve cost-effectiveness.

Mowing improves cost-effectiveness in prairie reconstruction by promoting early native plant establishment. Consistent with previous studies (Williams et al. 2007, 2010), we found that mowing promotes native plant establishment in prairie reconstruction. Mowing increased species richness, native grass stem density and native forb stem density during the early years of a prairie construction. Mowing also increased native plant cover and decreased annual weed cover during the early years of a prairie construction. By increasing forb stem density, mowing increased inflorescence production during the second and third growing seasons in the Pollinator and Diversity mixes. This acceleration of inflorescence production increases the lifetime value of these prairie reconstructions as pollinator habitat (Hopwood 2008; Pywell et al. 2011).

Potential funding and acreage cuts to the CRP program will limit its ability to provide ecosystem services on the landscape. Designing conservation practices that strive to accomplish multiple ecosystem services would be one way to combat the loss of these services. Our results demonstrate that a carefully designed seed mix, tailored to geographic and site conditions, can effectively produce multiple ecological benefits in a manner similar to two seed mixes designed to achieve a single ecological outcome. Future research will examine the long-term effects of our seed mix design and first-year mowing treatments.

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Appendix A. Species list and seeding rates of the Economy Mix (3:1 grass-to-forb seeding ratio) at the Northeast Research and Demonstration Farm.

Common Name	*Scientific Name*	*Functional group*	*PLS* m^{-2}	*% mix*
Canada wildrye	*Elymus canadensis*	grass (cool season)	46.3	10.75%
big bluestem	*Andropogon gerardii*	grass (warm season)	46.3	10.75%
side-oats grama	*Bouteloua curtipendula*	grass (warm season)	46.3	10.75%
switchgrass	*Panicum virgatum*	grass (warm season)	32.3	7.50%
little bluestem	*Schizachyrium scoparius*	grass (warm season)	46.3	10.75%
Indiangrass	*Sorghastrum nutans*	grass (warm season)	46.3	10.75%
tall dropseed	*Sporobolus compositus*	grass (warm season)	59.2	13.75%
Canada milkvetch	*Astragalus canadensis*	forb (legume)	10.8	2.50%

purple prairie clover	*Dalea purpurea*	forb (legume)	10.8	2.50%
prairie sage	*Artemisia ludoviciana*	forb	10.8	2.50%
tall boneset	*Eupatorium altissimum*	forb	5.4	1.25%
ox-eye sunflower	*Heliopsis helianthoides*	forb	5.4	1.25%
wild bergamot	*Monarda fistulosa*	forb	10.8	2.50%
stiff goldenrod	*Oligoneuron rigidum*	forb	5.4	1.25%
prairie cinquefoil	*Potentilla arguta*	forb	10.8	2.50%
yellow coneflower	*Ratibida pinnata*	forb	10.8	2.50%
black-eyed susan	*Rudbeckia hirta*	forb	5.4	1.25%
sweet coneflower	*Rudbeckia subtomentosa*	forb	8.1	1.88%
showy goldenrod	*Solidago speciosa*	forb	5.4	1.25%
New England aster	*Symphyotrichum novae-angliae*	forb	5.4	1.25%
golden alexander	*Zizia aurea*	forb	2.7	0.63%
	Overall Total:		430.4	

Appendix B. Species list and seeding rates of the Pollinator Mix (1:3 grass-to-forb seeding ratio) at the Northeast Research and Demonstration Farm.

Common Name	*Scientific Name*	*Functional group*	*PLS m^{-2}*	*% mix*
Junegrass	*Koeleria macrantha*	grass (cool season)	31.6	7.32%
big bluestem	*Andropogon gerardii*	grass (warm season)	3.6	0.82%
side-oats grama	*Bouteloua curtipendula*	grass (warm season)	3.4	0.80%
little bluestem	*Schizachyrium scoparius*	grass (warm season)	29.1	6.72%
tall dropseed	*Sporobolus compositus*	grass (warm season)	17.8	4.11%
prairie dropseed	*Sporobolus heterolepis*	grass (warm season)	3	0.70%
yellow fox sedge	*Carex vulpinoidea*	sedge	19.8	4.58%
Canada milkvetch	*Astragalus canadensis*	forb (legume)	3.3	0.77%

white wild indigo	*Baptisia alba*	forb (legume)	0.6	0.15%
white prairie clover	*Dalea candida*	forb (legume)	22.5	5.20%
purple prairie clover	*Dalea purpurea*	forb (legume)	25.2	5.82%
common milkweed	*Asclepias syriaca*	forb	1.6	0.37%
butterfly milkweed	*Asclepias tuberosa*	forb	3.4	0.80%
pale purple coneflower	*Echinacea pallida*	forb	6.2	1.44%
rattlesnake master	*Erynigium yuccifolium*	forb	8.9	2.07%
Sneezeweed	*Helenium autumnale*	forb	20.6	4.75%
Alumroot	*Heuchera richardsonii*	forb	27.7	6.39%
prairie blazingstar	*Liatris pycnostachya*	forb	8.7	2.02%
wild bergamot	*Monarda fistulosa*	forb	19.7	4.55%
stiff goldenrod	*Oligoneuron rigidum*	forb	8.1	1.87%
foxglove beardtongue	*Penstemon digitalis*	forb	10.3	2.39%
prairie phlox	*Phlox pilosa*	forb	0.3	0.07%
prairie cinquefoil	*Potentilla arguta*	forb	9.0	2.09%
common mountain mint	*Pycnanthemum virginianum*	forb	8.7	2.02%
yellow coneflower	*Ratibida pinnata*	forb	11.8	2.74%
black-eyed susan	*Rudbeckia hirta*	forb	25.5	5.90%
Rosinweed	*Silphium integrifolium*	forb	0.4	0.10%
compass plant	*Silphium laciniatum*	forb	0.8	0.17%
showy goldenrod	*Solidago speciosa*	forb	3.8	0.87%
heath aster	*Symphyotrichum ericoides*	forb	7.9	1.82%
smooth blue aster	*Symphyotrichum laeve*	forb	4.3	1.00%
New England aster	*Symphyotrichum novae-angliae*	forb	15.9	3.68%
sky-blue aster	*Symphyotrichum oolentangiense*	forb	3.1	0.72%
Ohio spiderwort	*Tradescantia ohiensis*	forb	4.7	1.09%
Ironweed	*Vernonia fasciculata*	forb	14.2	3.28%
Culver's root	*Veronicastrum virginicum*	forb	31.6	7.32%

prairie violet	*Viola pedatifida*	forb	1.1	0.25%
golden alexander	*Zizia aurea*	forb	14.1	3.26%
	Overall Total:		432.4	

Appendix C. Species list and seeding rates of the Diversity Mix (1:1 grass-to-forb seeding ratio) at the Northeast Research and Demonstration Farm.

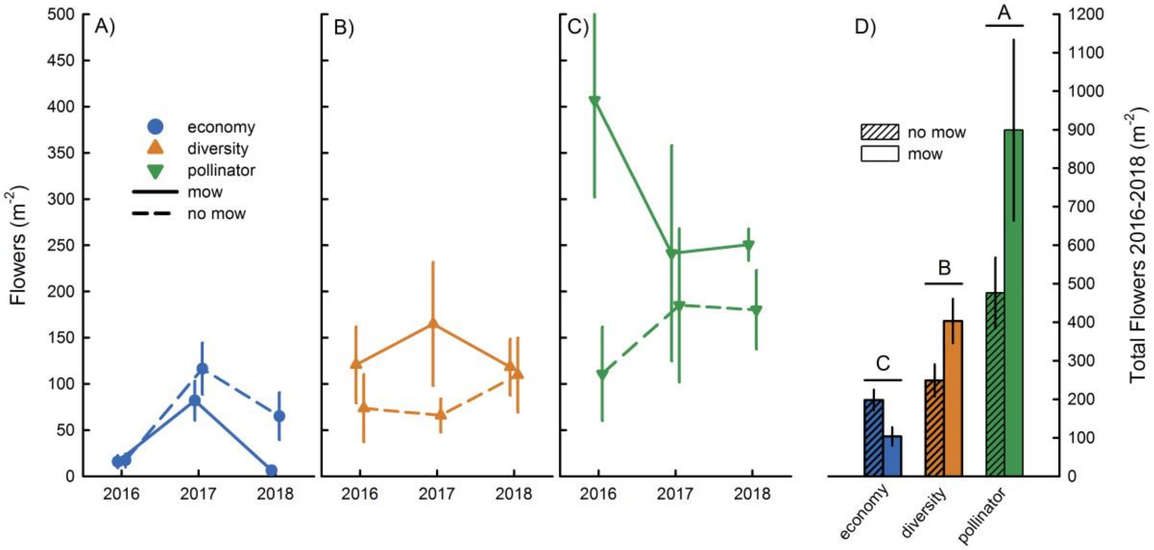
Common Name	*Scientific Name*	*Functional group*	*PLS m^{-2}*	*% mix*
prairie brome	*Bromus kalmii*	grass (cool season)	2.7	0.63%
Canada wildrye	*Elymus canadensis*	grass (cool season)	10.8	2.54%
fowl mannagrass	*Glyceria striata*	grass (cool season)	10.8	2.54%
big bluestem	*Andropogon gerardii*	grass (warm season)	21.5	5.07%
side-oats grama	*Bouteloua curtipendula*	grass (warm season)	32.3	7.61%
Switchgrass	*Panicum virgatum*	grass (warm season)	21.5	5.07%
little bluestem	*Schizachyrium scoparius*	grass (warm season)	21.5	5.07%
Indiangrass	*Sorghastrum nutans*	grass (warm season)	21.5	5.07%
tall dropseed	*Sporobolus compositus*	grass (warm season)	53.8	12.68%

prairie dropseed	*Sporobolus heterolepis*	grass (warm season)	2.7	0.63%
yellow fox sedge	*Carex annectens*	sedge	10.8	2.54%
Bicknell's sedge	*Carex bicknellii*	sedge	1.1	0.25%
plains oval sedge	*Carex brevior*	sedge	2.7	0.63%
heavy sedge	*Carex gravida*	sedge	0.2	0.05%
field oval sedge	*Carex molesta*	sedge	2.7	0.63%
Leadplant	*Amorpha canescens*	forb (legume)	2.2	0.51%
Canada milkvetch	*Astragalus canadensis*	forb (legume)	10.8	2.54%
white wild indigo	*Baptisia alba*	forb (legume)	0.2	0.05%
partridge pea	*Chamaecrista fasiculata*	forb (legume)	3.2	0.76%
purple prairie clover	*Dalea purpurea*	forb (legume)	10.8	2.54%
showy tick trefoil	*Desmodium canadense*	forb (legume)	1.6	0.38%
Illinois tick trefoil	*Desmodium illinoense*	forb (legume)	2.7	0.63%
round-headed bushclover	*Lespedeza capitata*	forb (legume)	0.5	0.13%
wild garlic	*Allium canadense*	forb	1.1	0.25%
Canada anemone	*Anemone canadensis*	forb	0.2	0.05%
Thimbleweed	*Anemone cylindrica*	forb	0.5	0.13%
prairie sage	*Artemisia ludoviciana*	forb	10.8	2.54%
swamp milkweed	*Asclepias incarnata*	forb	1.1	0.25%
common milkweed	*Asclepias syriaca*	forb	2.2	0.51%
butterfly milkweed	*Asclepias tuberosa*	forb	0.3	0.08%
whorled milkweed	*Asclepias verticillata*	forb	0.5	0.13%
New Jersey tea	*Ceanothus americanus*	forb	0.5	0.13%
prairie coreopsis	*Coreopsis palmata*	forb	0.4	0.10%
shootingstar	*Dodecatheon media*	forb	1.1	0.25%
pale purple coneflower	*Echinacea pallida*	forb	2.2	0.51%
rattlesnake master	*Erynigium yuccifolium*	forb	2.2	0.51%
tall boneset	*Eupatorium altissimum*	forb	2.7	0.63%
flowering spurge	*Euphorbia corollata*	forb	1.1	0.25%

grass-leaved goldenrod	*Euthamia graminifolia*	forb	10.8	2.54%
northern bedstraw	*Galium boreale*	forb	1.1	0.25%
bottle gentian	*Gentiana andrewsii*	forb	5.4	1.27%
bigtooth sunflower	*Helianthus grosseserratus*	forb	1.6	0.38%
prairie sunflower	*Helianthus laetiflorus*	forb	0.2	0.05%
ox-eye sunflower	*Heliopsis helianthoides*	forb	5.4	1.27%
prairie blazingstar	*Liatris pycnostachya*	forb	1.1	0.25%
Michigan lily	*Lilium michiganense*	forb	0.1	0.03%
great blue lobelia	*Lobelia siphilitica*	forb	10.8	2.54%
wild bergamot	*Monarda fistulosa*	forb	8.1	1.90%
stiff goldenrod	*Oligoneuron rigidum*	forb	8.1	1.90%
wild quinine	*Parthenium integrifolium*	forb	1.1	0.25%
foxglove beardtongue	*Penstemon digitalis*	forb	10.8	2.54%
prairie phlox	*Phlox pilosa*	forb	0.2	0.05%
prairie cinquefoil	*Potentilla arguta*	forb	10.8	2.54%
hairy mountain mint	*Pycnanthemum pilosum*	forb	8.1	1.90%
slender mountain mint	*Pycnanthemum tenuifolium*	forb	10.8	2.54%
common mountain mint	*Pycnanthemum virginianum*	forb	10.8	2.54%
yellow coneflower	*Ratibida pinnata*	forb	10.8	2.54%
black-eyed susan	*Rudbeckia hirta*	forb	8.1	1.90%
sweet coneflower	*Rudbeckia subtomentosa*	forb	8.1	1.90%
rosinweed	*Silphium integrifolium*	forb	0.2	0.05%
compass plant	*Silphium laciniatum*	forb	0.1	0.03%
showy goldenrod	*Solidago speciosa*	forb	8.1	1.90%
smooth blue aster	*Symphyotrichum laeve*	forb	5.4	1.27%
New England aster	*Symphyotrichum novae-angliae*	forb	5.4	1.27%
sky-blue aster	*Symphyotrichum oolentangiense*	forb	2.7	0.63%
purple meadow rue	*Thalictrum dasycarpum*	forb	0.5	0.13%
prairie spiderwort	*Tradescantia bracteata*	forb	0.5	0.13%

Ohio spiderwort	*Tradescantia ohiensis*	forb	1.1	0.25%
ironweed	*Vernonia fasciculata*	forb	2.7	0.63%
Culver's root	*Veronicastrum virginicum*	forb	5.4	1.27%
golden alexander	*Zizia aurea*	forb	2.7	0.63%
	Overall Total:		441.8	

Appendix D. Inflorescence production in the Economy (A), Diversity (B), and Pollinator (C) mixes in each surveyed year. Mowed plots are indicated with a solid line and plots that were not mowed are indicated with a dashed line. Cumulative inflorescence production (2016-2018) is provided in panel D.



A)
B)
C)
D)
Flowers (m^-2)
500
450
400
350
300
250
200
150
100
50
0
economy
diversity
pollinator
mow
no mow
2016
2017
2018
no mow
mow
A
B
C
Total Flowers 2016-2018 (m^-2)
1200
1100
1000
900
800
700
600
500
400
300
200
100
0
economy
diversity
pollinator