Evaluating the cost-effectiveness of CRP seed mixes for supporting wild bees

Eric Lonsdorf[1] and Kimiora Ward[2, 3]

1. Institute on the Environment, University of Minnesota, St. Paul, MN
2. Department of Entomology and Nematology, University of California, Davis, CA
3. Institute for Applied Ecology, Southwest Office, Santa Fe, NM (current), kimiora@appliedecology.org

July 11, 2019

Summary

Pollinator plantings can be expensive and seed cost is consistently identified as a barrier to implementation of CP-42 or other habitat practices designed to support wildlife or ecosystem functions. We evaluated the effectiveness of commercially available seed mixtures, including those that were designed for CRP cover practices, for supporting pollinators using newly developed methods (Williams and Lonsdorf 2018) that incorporates observations of the benefits of particular plants to bees and seed costs of each plant species. We tested the process in three parts of the country where we have sufficient data: California, Minnesota and Pennsylvania/New Jersey. We found that one could save from $200 to $900 per acre and still support the same number of bees. The approach of maximizing the benefits of a mix at the least cost are generalizable to multiple objectives and could be applied to CRP cover practices.

Introduction

Challenges to honey bee health and global declines in wild pollinators have led to increased awareness of the need to restore floral-rich habitat on both public and private lands. The Pollinator Health Task Force (2015) called for the establishment or enhancement of 7 million acres of pollinator habitat by 2020, and multiple initiatives by USDA and partnerships between private companies and NGOs are focused on creation or restoration of pollinator habitat. While the Pollinator Habitat Initiative practice (CP42) of the Farm Service Agency's

Conservation Reserve Program specifically targets support of honey bees and diverse wild pollinator communities, all cover practices could be modified to support pollinators. However, pollinator plantings can be expensive and seed cost is consistently identified as a barrier to implementation of CP42 or other habitat practices designed to support wildlife or ecosystem functions. The use of seed mixtures that emphasize plant species that demonstrably support pollinators, bloom at the right time and are compatible with land management practices can increase cost effectiveness of habitat plantings and encourage the native seed market. Recent work aligning plant-pollinator interaction data with the species composition of wildflower mixtures used in pollinator restoration plantings demonstrates the potential for increasing cost-effectiveness of these mixes by including plants that support the greatest diversity of bees and excluding those providing no benefit (Harmon-Threatt and Hendrix 2015, Otto et al. 2017). Computational methods can be applied to identify plant mixes that optimize one or multiple criteria when designing seed mixes (M'Gonigle et al. 2015; Williams and Lonsdorf 2018), such that bee diversity can be maximized while minimizing cost. We evaluated the effectiveness of commercially available seed mixtures, including those that were designed for CRP cover practices, for supporting pollinators using newly developed methods (Williams and Lonsdorf 2018 that incorporate observations of the benefits of particular plants to bees and seed costs of each plant species. We contacted seed vendors from three regions in the US and gathered data on mixes they sell, including those used in CRP plantings as well as the cost of the mix. Then we used knowledge of plant-pollinator networks to predict how many bees those mixes support. Finally, we applied a genetic algorithm to determine if we could create seed mixes that are either cheaper, support more bee species or both.

Approach to problem

Our goal is to develop a process that facilitates more cost-effective enhancement practices supported by CRP and other federal programs designed to support pollinators. We tested the process in three parts of the country where we have sufficient data: California, Minnesota and Pennsylvania/New Jersey. In each of these regions, we have good knowledge and data on plant-pollinator interactions. We used these data to build and test a three-step approach to evaluation and improvement.

First, we evaluated existing mixes' ability to support bees. We gathered existing information on the seed mixtures currently being used and identify the source vendor of those seed mixes. Co-PI Kimiora interviewed NRCS staff to determine what seed mixes are in use for a variety of CRP-like cover practices in each region, and consulted seed vendors to quantify the relative costs of each species in the mix. Using plant-pollinator interaction data from previous studies (Forrest 2015; Williams and Ward in preparation for CA; Cariveau and Bruninga-Scolar for MN and PA) we quantified the relative contribution of each mix to supporting a diverse wild bee community. Second, we applied a recently created seed mix design model (Williams and Lonsdorf 2018) to suggest cost-effective regional plant mixes based on expected pricing to improve the mix's ability to support pollinators at reduced costs. The base model predicts the ability of a plant species mix to support wild bees. The model integrates 4 types of input: (1) the phenology of individual bee species that are the targets to be supported by a plant mix; (2) the phenologies of potential plant species; (3) a plant-pollinator interaction matrix identifying those plant species that are used as pollen and/or nectar resources by each bee species; (4) the expected cost to include a plant species in the mix. We use the model to design cost-effective mixes using a genetic algorithm that applies principles of evolution to solve for a mix that supports the most bees given a budget. Third, the results of steps one and two, allows us to compare the costs and benefits of the original mixes to the optimized mixes. Such data can then be used to compare the costs and benefits of alternative sets of plant species that fully support a bee, or set of bees, defined by the goal. The same approach can be generalized to include additional plant or bee traits that might influence selection toward a defined goal (e.g., whether a given plant species is drought tolerant or whether a given bee is a known to pollinate a crop of interest). We quantified the cost-savings and added benefits of this analysis.

The previous work by Williams and Lonsdorf (2018) treated the decision about plant species to include as a binary problem, i.e. whether to include a species or not, rather than a question of how much. In this previous work, the cost of including a species was fixed and its ability to support pollinators was not dependent on the amount planted. The analysis was focused on the set of species included, rather than how much of each to include. We planned to follow this approach but a preliminary analysis of vendor mixes using a binary approach revealed that many mixes were cheaper due to the amount of seed used per acre in addition the choice of species used. Thus we amended the approach so that the decision for each species was how much to include in the mix rather than simply whether or not to include it. While there is a general belief that increased seeding density leads to increased plant and flowering, there are few quantitative data to support this. So we have used the assumptions that increasing floral density increases with seeding rates and that increasing floral density increases the likelihood that bees are supported.

The CP42 Pollinator Habitat Initiative began in 2012, and by Sep 2018 there were 507,439 cumulative acres installed on CRP-enrolled lands nationwide (Conservation Reserve Program Monthly Summary Sept 2018). Our three focal regions differ substantially in CP42 acreage (Figure 1), and this resulted in large differences in the numbers of seed vendors focused on providing seed mixes for pollinator habitat, as well as in the availability of CRP-allowable pre-designed mixes.

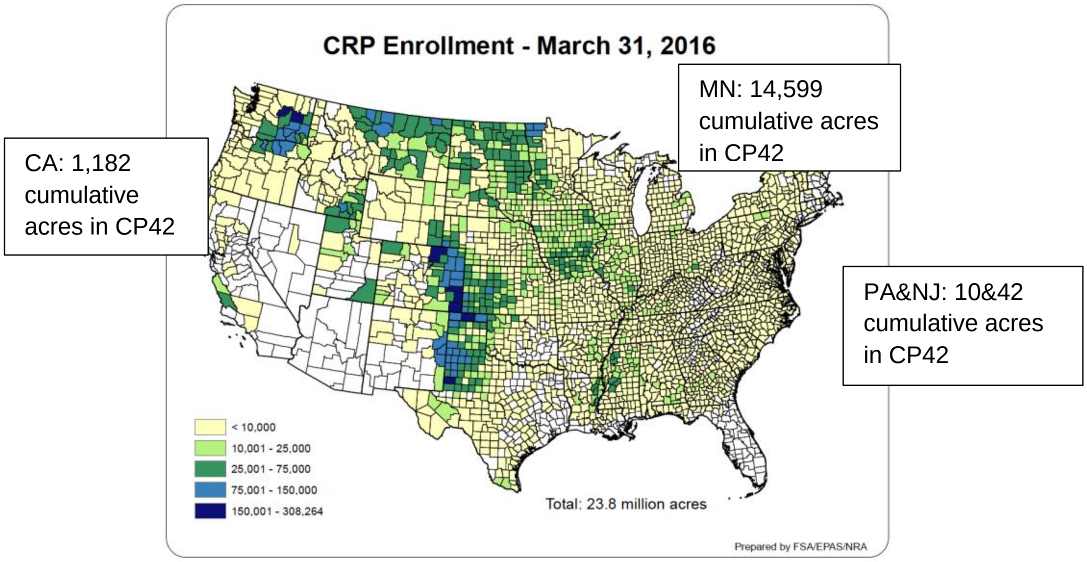
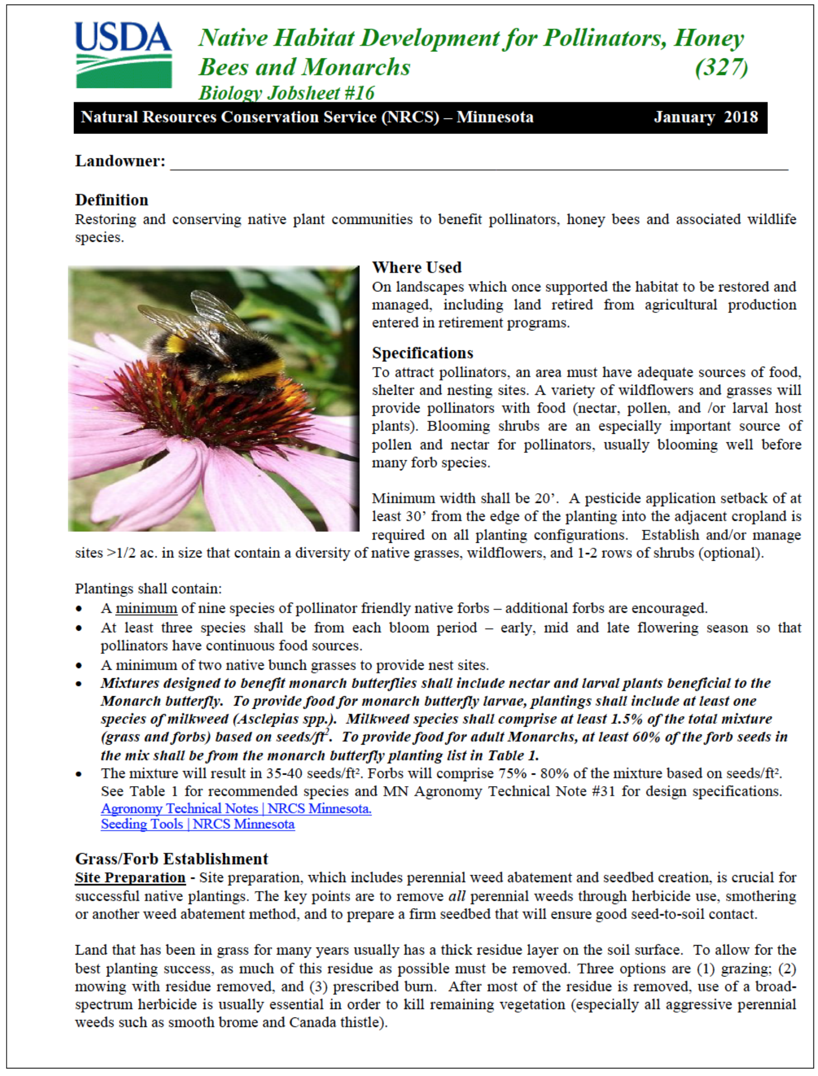


Figure 1. Acres enrolled in CRP nationwide, with cumulative acreage of CP42 pollinator plantings installed as of September 2018 in the three focal regions

Minnesota

Minnesota had 14,995 acres of CP42 pollinator habitat installed on CRP-enrolled lands as of September 2018. Requirements of CP42 in Minnesota specify that plantings shall contain a minimum of 9 species of pollinator friendly forbs, with additional forbs encouraged. At least three species shall be from each bloom period - early, mid and late flowering season so that pollinators have continuous food sources. A minimum of two native bunch grasses are to provide nest sites. The mixture must result in 35-40 seeds/sf, with forbs comprising 75-80% of the mixture based on seeds/sf. Individual forb species are not to exceed 20% of the forb component by seeds/sf. CRP practices aimed at erosion control or wildlife habitat have much lower requirements for the inclusion of forbs, with CP2 -- Establishment of Permanent Native Grasses and CP4d -- Permanent Wildlife Habitat requiring 10% forbs and CP25 -- Rare and Declining Habitat requiring 40% forbs. Nevertheless these practices could be optimized for benefit to pollinators through intelligent selection of cost-effective forb species, thus adding benefit to pollinators while meeting the goals of erosion control and habitat for other wildlife.



Native Habitat Development for Pollinators, Honey Bees and Monarchs (327)
Biology Jobsheet #16

Natural Resources Conservation Service (NRCS) – Minnesota **January 2018**

Landowner: ____________________

Definition
Restoring and conserving native plant communities to benefit pollinators, honey bees and associated wildlife species.

Where Used
On landscapes which once supported the habitat to be restored and managed, including land retired from agricultural production entered in retirement programs.

Specifications
To attract pollinators, an area must have adequate sources of food, shelter and nesting sites. A variety of wildflowers and grasses will provide pollinators with food (nectar, pollen, and /or larval host plants). Blooming shrubs are an especially important source of pollen and nectar for pollinators, usually blooming well before many forb species.

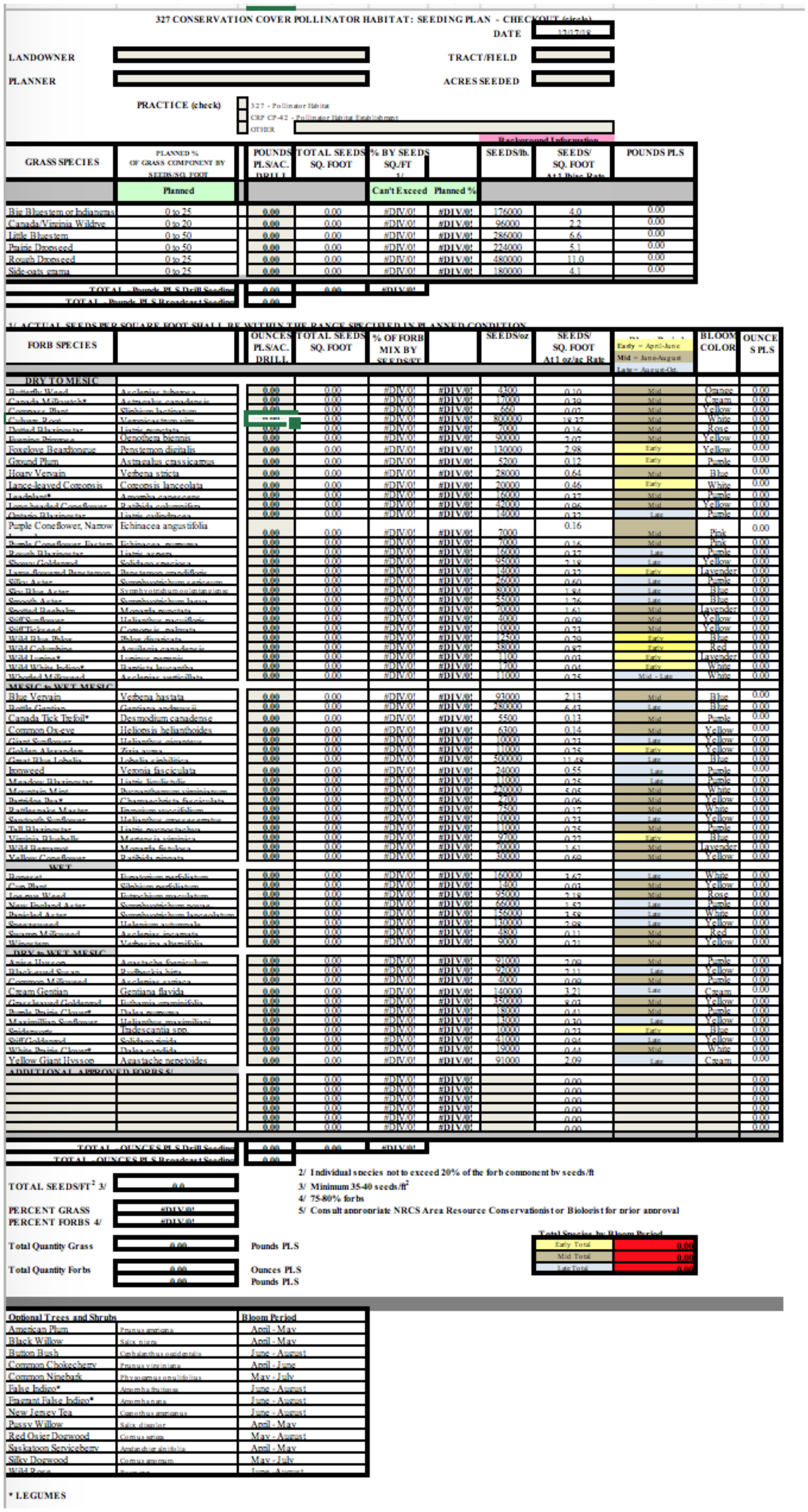
Minimum width shall be 20'. A pesticide application setback of at least 30' from the edge of the planting into the adjacent cropland is required on all planting configurations. Establish and/or manage sites >1/2 ac. in size that contain a diversity of native grasses, wildflowers, and 1-2 rows of shrubs (optional).

Plantings shall contain:
- A minimum of nine species of pollinator friendly native forbs – additional forbs are encouraged.
- At least three species shall be from each bloom period – early, mid and late flowering season so that pollinators have continuous food sources.
- A minimum of two native bunch grasses to provide nest sites.
- ***Mixtures designed to benefit monarch butterflies shall include nectar and larval plants beneficial to the Monarch butterfly. To provide food for monarch butterfly larvae, plantings shall include at least one species of milkweed (Asclepias spp.). Milkweed species shall comprise at least 1.5% of the total mixture (grass and forbs) based on seeds/ft^2. To provide food for adult Monarchs, at least 60% of the forb seeds in the mix shall be from the monarch butterfly planting list in Table 1.***
- The mixture will result in 35-40 seeds/ft^2. Forbs will comprise 75% - 80% of the mixture based on seeds/ft^2. See Table 1 for recommended species and MN Agronomy Technical Note #31 for design specifications. Agronomy Technical Notes | NRCS Minnesota. Seeding Tools | NRCS Minnesota

Grass/Forb Establishment
Site Preparation - Site preparation, which includes perennial weed abatement and seedbed creation, is crucial for successful native plantings. The key points are to remove *all* perennial weeds through herbicide use, smothering or another weed abatement method, and to prepare a firm seedbed that will ensure good seed-to-soil contact.

Land that has been in grass for many years usually has a thick residue layer on the soil surface. To allow for the best planting success, as much of this residue as possible must be removed. Three options are (1) grazing; (2) mowing with residue removed, and (3) prescribed burn. After most of the residue is removed, use of a broad-spectrum herbicide is usually essential in order to kill remaining vegetation (especially all aggressive perennial weeds such as smooth brome and Canada thistle).

Rather than purchasing pre-mixed CP42 mixes, landowners typically develop seed mixes at the enrollment level in consultation with NRCS staff and seed vendors. These mixes are tailored to the soils, water availability, management history and weed pressure on the individual site, as well as being influenced by the availability and market for seed of each native species in the year of establishment. State Biologist Mark Oja and other NRCS staff in Minnesota have developed a sophisticated seed calculator tool to assist vendors and with the design of seed mixes to ensure specifications are met (Figure 2).



327 CONSERVATION COVER POLLINATOR HABITAT: SEEDING PLAN - CHECKOUT (circle)

DATE 12/17/18

LANDOWNER

TRACT/FIELD

PLANNER

ACRES SEEDED

PRACTICE (check)
- 327 - Pollinator Habitat
- CRP CP-42 - Pollinator Habitat Establishment
- OTHER

Background Information

GRASS SPECIES	PLANNED % OF GRASS COMPONENT BY SEEDS/SQ. FOOT	POUNDS PLS/AC. DRILL	TOTAL SEEDS SQ. FOOT	% BY SEEDS SQ./FT 1/		SEEDS/lb.	SEEDS/ SQ. FOOT At 1 lb/ac Rate	POUNDS PLS
	Planned			Can't Exceed	Planned %			
Big Bluestem or Indiangrass	0 to 25	0.00	0.00	#DIV/0!	#DIV/0!	176000	4.0	0.00
Canada/Virginia Wildrye	0 to 20	0.00	0.00	#DIV/0!	#DIV/0!	96000	2.2	0.00
Little Bluestem	0 to 50	0.00	0.00	#DIV/0!	#DIV/0!	286000	6.6	0.00
Prairie Dropseed	0 to 50	0.00	0.00	#DIV/0!	#DIV/0!	224000	5.1	0.00
Rough Dropseed	0 to 25	0.00	0.00	#DIV/0!	#DIV/0!	480000	11.0	0.00
Side-oats grama	0 to 25	0.00	0.00	#DIV/0!	#DIV/0!	180000	4.1	0.00
TOTAL - Pounds PLS Drill Seeding		0.00	0.00	#DIV/0!				
TOTAL - Pounds PLS Broadcast Seeding		0.00						

1/ ACTUAL SEEDS PER SQUARE FOOT SHALL BE WITHIN THE RANGE SPECIFIED IN PLANNED CONDITION

FORB SPECIES		OUNCES PLS/AC. DRILL	TOTAL SEEDS SQ. FOOT	% OF FORB MIX BY SEEDS/FT		SEEDS/oz	SEEDS/ SQ. FOOT At 1 oz/ac Rate	Bloom Period (Early = April-June; Mid = June-August; Late = August-Oct.)	BLOOM COLOR	OUNCES PLS
DRY TO MESIC										
Butterfly Weed	Asclepias tuberosa	0.00	0.00	#DIV/0!	#DIV/0!	4300	0.10	Mid	Orange	0.00
Canada Milkvetch*	Astragalus canadensis	0.00	0.00	#DIV/0!	#DIV/0!	17000	0.39	Mid	Cream	0.00
Compass Plant	Silphium laciniatum	0.00	0.00	#DIV/0!	#DIV/0!	660	0.02	Mid	Yellow	0.00
Culver's Root	Veronicastrum virg	[illegible]	0.00	#DIV/0!	#DIV/0!	800000	18.37	Mid	White	0.00
Dotted Blazingstar	Liatris punctata	0.00	0.00	#DIV/0!	#DIV/0!	7000	0.16	Mid	Rose	0.00
Evening Primrose	Oenothera biennis	0.00	0.00	#DIV/0!	#DIV/0!	90000	2.07	Mid	Yellow	0.00
Foxglove Beardtongue	Penstemon digitalis	0.00	0.00	#DIV/0!	#DIV/0!	130000	2.98	Early	Yellow	0.00
Ground Plum	Astragalus crassicarpus	0.00	0.00	#DIV/0!	#DIV/0!	5200	0.12	Early	Purple	0.00
Hoary Vervain	Verbena stricta	0.00	0.00	#DIV/0!	#DIV/0!	28000	0.64	Mid	Blue	0.00
Lance-leaved Coreopsis	Coreopsis lanceolata	0.00	0.00	#DIV/0!	#DIV/0!	20000	0.46	Early	White	0.00
Leadplant*	Amorpha canescens	0.00	0.00	#DIV/0!	#DIV/0!	16000	0.37	Mid	Purple	0.00
Long-headed Coneflower	Ratibida columnifera	0.00	0.00	#DIV/0!	#DIV/0!	42000	0.96	Mid	Yellow	0.00
Ontario Blazingstar	Liatris cylindracea	0.00	0.00	#DIV/0!	#DIV/0!	14000	0.32	Late	Purple	0.00
Purple Coneflower, Narrow leaved	Echinacea angustifolia	0.00	0.00	#DIV/0!	#DIV/0!	7000	0.16	Mid	Pink	0.00
Purple Coneflower, Eastern	Echinacea purpurea	0.00	0.00	#DIV/0!	#DIV/0!	7000	0.16	Mid	Pink	0.00
Rough Blazingstar	Liatris aspera	0.00	0.00	#DIV/0!	#DIV/0!	16000	0.37	Late	Purple	0.00
Showy Goldenrod	Solidago speciosa	0.00	0.00	#DIV/0!	#DIV/0!	95000	2.18	Late	Yellow	0.00
Large-flowered Penstemon	Penstemon grandiflorus	0.00	0.00	#DIV/0!	#DIV/0!	14000	0.32	Early	Lavender	0.00
Silky Aster	Symphyotrichum sericeum	0.00	0.00	#DIV/0!	#DIV/0!	26000	0.60	Late	Purple	0.00
Sky Blue Aster	Symphyotrichum oolentangiense	0.00	0.00	#DIV/0!	#DIV/0!	80000	1.84	Late	Blue	0.00
Smooth Aster	Symphyotrichum laeve	0.00	0.00	#DIV/0!	#DIV/0!	55000	1.26	Late	Blue	0.00
Spotted Beebalm	Monarda punctata	0.00	0.00	#DIV/0!	#DIV/0!	70000	1.61	Mid	Lavender	0.00
Stiff Sunflower	Helianthus pauciflorus	0.00	0.00	#DIV/0!	#DIV/0!	4000	0.09	Mid	Yellow	0.00
Stiff Tickseed	Coreopsis palmata	0.00	0.00	#DIV/0!	#DIV/0!	10000	0.23	Mid	Yellow	0.00
Wild Blue Phlox	Phlox divaricata	0.00	0.00	#DIV/0!	#DIV/0!	12500	0.29	Early	Blue	0.00
Wild Columbine	Aquilegia canadensis	0.00	0.00	#DIV/0!	#DIV/0!	38000	0.87	Early	Red	0.00
Wild Lupine*	Lupinus perennis	0.00	0.00	#DIV/0!	#DIV/0!	1100	0.03	Early	Lavender	0.00
Wild White Indigo*	Baptisia leucantha	0.00	0.00	#DIV/0!	#DIV/0!	1700	0.04	Early	White	0.00
Whorled Milkweed	Asclepias verticillata	0.00	0.00	#DIV/0!	#DIV/0!	11000	0.25	Mid - Late	White	0.00
MESIC to WET MESIC										
Blue Vervain	Verbena hastata	0.00	0.00	#DIV/0!	#DIV/0!	93000	2.13	Mid	Blue	0.00
Bottle Gentian	Gentiana andrewsii	0.00	0.00	#DIV/0!	#DIV/0!	280000	6.43	Late	Blue	0.00
Canada Tick Trefoil*	Desmodium canadense	0.00	0.00	#DIV/0!	#DIV/0!	5500	0.13	Mid	Purple	0.00
Common Ox-eye	Heliopsis helianthoides	0.00	0.00	#DIV/0!	#DIV/0!	6300	0.14	Mid	Yellow	0.00
Giant Sunflower	Helianthus giganteus	0.00	0.00	#DIV/0!	#DIV/0!	10000	0.23	Late	Yellow	0.00
Golden Alexanders	Zizia aurea	0.00	0.00	#DIV/0!	#DIV/0!	11000	0.25	Early	Yellow	0.00
Great Blue Lobelia	Lobelia siphilitica	0.00	0.00	#DIV/0!	#DIV/0!	500000	11.48	Late	Blue	0.00
Ironweed	Veronia fasciculata	0.00	0.00	#DIV/0!	#DIV/0!	24000	0.55	Late	Purple	0.00
Meadow Blazingstar	Liatris ligulistylis	0.00	0.00	#DIV/0!	#DIV/0!	11000	0.25	Late	Purple	0.00
Mountain Mint	Pycnanthemum virginianum	0.00	0.00	#DIV/0!	#DIV/0!	220000	5.05	Mid	White	0.00
Partridge Pea*	Chamaechrista fasciculata	0.00	0.00	#DIV/0!	#DIV/0!	2700	0.06	Mid	Yellow	0.00
Rattlesnake Master	Eryngium yuccifolium	0.00	0.00	#DIV/0!	#DIV/0!	7500	0.17	Mid	White	0.00
Sawtooth Sunflower	Helianthus grosseserratus	0.00	0.00	#DIV/0!	#DIV/0!	10000	0.23	Late	Yellow	0.00
Tall Blazingstar	Liatris pycnostachya	0.00	0.00	#DIV/0!	#DIV/0!	11000	0.25	Mid	Purple	0.00
Virginia Bluebells	Mertensia virginica	0.00	0.00	#DIV/0!	#DIV/0!	9700	0.22	Early	Blue	0.00
Wild Bergamot	Monarda fistulosa	0.00	0.00	#DIV/0!	#DIV/0!	70000	1.61	Mid	Lavender	0.00
Yellow Coneflower	Ratibida pinnata	0.00	0.00	#DIV/0!	#DIV/0!	30000	0.69	Mid	Yellow	0.00
WET										
Boneset	Eupatorium perfoliatum	0.00	0.00	#DIV/0!	#DIV/0!	160000	3.67	Late	White	0.00
Cup Plant	Silphium perfoliatum	0.00	0.00	#DIV/0!	#DIV/0!	1400	0.03	Mid	Yellow	0.00
Joe-pye Weed	Eutrochium maculatum	0.00	0.00	#DIV/0!	#DIV/0!	95000	2.18	Mid	Rose	0.00
New England Aster	Symphyotrichum novae-	0.00	0.00	#DIV/0!	#DIV/0!	66000	1.52	Late	Purple	0.00
Panicled Aster	Symphyotrichum lanceolatum	0.00	0.00	#DIV/0!	#DIV/0!	156000	3.58	Late	White	0.00
Sneezeweed	Helenium autumnale	0.00	0.00	#DIV/0!	#DIV/0!	130000	2.98	Late	Yellow	0.00
Swamp Milkweed	Asclepias incarnata	0.00	0.00	#DIV/0!	#DIV/0!	4800	0.11	Mid	Red	0.00
Wingstem	Verbesina alternifolia	0.00	0.00	#DIV/0!	#DIV/0!	9000	0.21	Mid	Yellow	0.00
DRY to WET MESIC										
Anise Hyssop	Agastache foeniculum	0.00	0.00	#DIV/0!	#DIV/0!	91000	2.09	Mid	Purple	0.00
Black-eyed Susan	Rudbeckia hirta	0.00	0.00	#DIV/0!	#DIV/0!	92000	2.11	Late	Yellow	0.00
Common Milkweed	Asclepias syriaca	0.00	0.00	#DIV/0!	#DIV/0!	4000	0.09	Mid	Purple	0.00
Cream Gentian	Gentiana flavida	0.00	0.00	#DIV/0!	#DIV/0!	140000	3.21	Late	Cream	0.00
Grass-leaved Goldenrod	Euthamia graminifolia	0.00	0.00	#DIV/0!	#DIV/0!	350000	8.03	Mid	Yellow	0.00
Purple Prairie Clover*	Dalea purpurea	0.00	0.00	#DIV/0!	#DIV/0!	18000	0.41	Mid	Purple	0.00
Maximillian Sunflower	Helianthus maximiliani	0.00	0.00	#DIV/0!	#DIV/0!	13000	0.30	Late	Yellow	0.00
Spiderworts	Tradescantia spp.	0.00	0.00	#DIV/0!	#DIV/0!	10000	0.23	Early	Blue	0.00
Stiff Goldenrod	Solidago rigida	0.00	0.00	#DIV/0!	#DIV/0!	41000	0.94	Late	Yellow	0.00
White Prairie Clover*	Dalea candida	0.00	0.00	#DIV/0!	#DIV/0!	19000	0.44	Mid	White	0.00
Yellow Giant Hyssop	Agastache nepetoides	0.00	0.00	#DIV/0!	#DIV/0!	91000	2.09	Late	Cream	0.00
ADDITIONAL APPROVED FORBS 5/										
		0.00	0.00	#DIV/0!	#DIV/0!		0.00			0.00
		0.00	0.00	#DIV/0!	#DIV/0!		0.00			0.00
		0.00	0.00	#DIV/0!	#DIV/0!		0.00			0.00
		0.00	0.00	#DIV/0!	#DIV/0!		0.00			0.00
		0.00	0.00	#DIV/0!	#DIV/0!		0.00			0.00
		0.00	0.00	#DIV/0!	#DIV/0!		0.00			0.00
TOTAL - OUNCES PLS Drill Seeding		0.00	0.00	#DIV/0!						
TOTAL - OUNCES PLS Broadcast Seeding		0.00								

TOTAL SEEDS/FT² 3/ 0.0

PERCENT GRASS #DIV/0!
PERCENT FORBS 4/ #DIV/0!

Total Quantity Grass 0.00 Pounds PLS

Total Quantity Forbs 0.00 Ounces PLS; 0.00 Pounds PLS

2/ Individual species not to exceed 20% of the forb component by seeds/ft
3/ Minimum 35-40 seeds/ft²
4/ 75-80% forbs
5/ Consult appropriate NRCS Area Resource Conservationist or Biologist for prior approval

Total Species by Bloom Period

Early Total	0.00
Mid Total	0.00
Late Total	0.00

Optional Trees and Shrubs		Bloom Period
American Plum	Prunus americana	April - May
Black Willow	Salix nigra	April - May
Button Bush	Cephalanthus occidentalis	June - August
Common Chokecherry	Prunus virginiana	April - June
Common Ninebark	Physocarpus opulifolius	May - July
False Indigo*	Amorpha fruticosa	June - August
Fragrant False Indigo*	Amorpha nana	June - August
New Jersey Tea	Ceanothus americanus	June - August
Pussy Willow	Salix discolor	April - May
Red Osier Dogwood	Cornus sericea	May - August
Saskatoon Serviceberry	Amelanchier alnifolia	April - May
Silky Dogwood	Cornus amomum	May - July
Wild Rose	Rosa spp.	June - August

* LEGUMES

Figure 2. Seed mix calculator tool for CP42 plantings in Minnesota

We interviewed 20 vendors selling pollinator mixes for restoration plantings in Minnesota, and although the majority of CRP seed mixes are individually tailored, we were able to obtain data from six of these vendors on the species composition and costs of federal cost share and other pollinator mixes that major vendors pre-mix and make widely available (Table 1).

Table 1. Vendors surveyed in each state. Bolded text indicates vendors that provided detailed mix cost and species composition information

Vendors Interviewed		
CA	MN	PA/NJ
5	19	6
• **Hedgerow Farms**	• **Shooting Star Natives**	• **Ernst Conservation Seed Co.**
• **S & S Seeds**	• **Prairie Moon Native Nursery**	• **Millborn Seed**
• Pacific Coast Seed	• **Minnesota Native Landscapes**	• **Pheasants Forever**
• Larner Seed	• **Millborn Seed**	• **Pinelands Nursery**
	• **Pheasants Forever**	• Roundstone Seed
	• **Prairie Land Management, Inc**	• Chesapeake Valley Seed
	• Albert Lea	
	• Mohn Seed Co.	
	• Prairie Land Professionals	
	• Nativescapes	
	• Prairie Nursery	
	• Vermillion Elevator Inc.	
	• Werber Seed Company	
	• Allendan Seed	
	• Feder's Prairie Seed Co.	
	• Applewood Seed	
	• Out Back Nursery and Landscaping	
	• Farmer's Mill Elevator, Inc.	
	• Prairie Frontier	

Vendors provided cost and species composition information for 15 seed mixes meeting CP42 specifications in Minnesota (Table 2), as well as 11 CP25 mixes and several other CRP mixes

designed for wildlife habitat and erosion control. In addition to these, we obtained data on four seed mixes vendors specially designed to promote pollinators as well as 27 forb-rich mixes targeted for prairies or meadows more generally. This wide diversity of mixes designed to meet varying objectives allows us to compare the benefits to pollinators from mixes with varying costs and potentially to other ecosystem services if additional trait data were included (Barak et al In prep).

Table 2. Number of mixes obtained in each state that met requirements for federal cost share or that were designed by seed vendors for diverse floral resouces or specifically for pollinators

Number of seed mixes	CA	MN	PA/NJ	
Federal Cost Share				
CP42		15	1	
NRCS Practice Standard 327 (EQIP)	3		8	
CP25		11		
CP4d		2		
CP2		7		
CP1		2		
CREP		1		
Vendor mixes				
Pollinator	1	4	13	
Prairie/meadow	10	27	11	
	14	69	33	116

These 69 pollinator mixes provided information on 183 forb species and 6 shrubs available for use in restorations (Table 3). Of those species used in available commercial mixes, 72 were also included in the plant-pollinator interaction data provided by our collaborators at the University of Minnesota. We use these 72 species in the analyses. These species make up more than 75% of the mix-by-species combinations used in the 69 mixes.

Table 3. Forbs and flowering woody species included in Minnesota CRP and vendor-designed pollinator and other forb-rich mixes. Species with an asterisk also occurred in the plant-pollinator interaction data, and were included in the optimization modeling. Nomenclature follows USDA PLANTS database standards as of Nov 16, 2018.

Achillea millefolium*	Crotalaria sagittalis	Lobelia inflata	Ruellia caroliniensis ssp. ciliosa var. cinerascens
Acorus americanus	Dalea candida*	Lobelia siphilitica*	Sagittaria latifolia
Agastache foeniculum*	Dalea foliosa	Lobelia spicata*	Scrophularia lanceolata*
Agastache nepetoides	Dalea purpurea*	Lupinus perennis*	Senna hebecarpa*
Agastache scrophulariifolia*	Desmanthus illinoensis	Lycopus americanus	Senna marilandica
Alisma subcordatum	Desmodium canadense*	Lysimachia quadriflora	Silene regia
Allium canadense	Desmodium illinoense	Lythrum alatum	Silene stellata
Allium cernuum*	Dodecatheon meadia	Maianthemum racemosum ssp. racemosum	Silphium compositum var. reniforme
Allium stellatum*	Doellingeria umbellata*	Medicago sativa*	Silphium integrifolium*
Ammannia coccinea	Echinacea angustifolia*	Mentha arvensis*	Silphium laciniatum
Amorpha canescens*	Echinacea pallida*	Mimulus ringens*	Silphium perfoliatum*
Anemone canadensis*	Echinacea paradoxa	Monarda bradburiana*	Sisyrinchium angustifolium*
Anemone cylindrica	Echinacea purpurea*	Monarda punctata*	Solidago juncea*
Anemone virginiana	Echinacea tennesseensis	Napaea dioica	Solidago nemoralis*
Angelica atropurpurea	Eryngium yuccifolium*	Oenothera biennis*	Solidago speciosa*
Apocynum cannabinum*	Eupatorium perfoliatum*	Oenothera clelandii*	Sparganium eurycarpum
Aquilegia canadensis*	Euphorbia corollata*	Oligoneuron riddellii	Symphyotrichum ericoides*
Arnoglossum atriplicifolium*	Euthamia graminifolia var. graminifolia	Oligoneuron rigidum*	Symphyotrichum laeve*
Arnoglossum reniforme	Eutrochium maculatum*	Oligoneuron rigidum var. rigidum*	Symphyotrichum laeve var. laeve
Artemisia ludoviciana	Gaura biennis	Parthenium integrifolium	Symphyotrichum lanceolatum*
Asclepias incarnata*	Gaura longiflora	Pedicularis canadensis*	Symphyotrichum lateriflorum*
Asclepias speciosa*	Gentiana alba	Pedicularis lanceolata*	Symphyotrichum novae-angliae*
Asclepias syriaca*	Gentiana andrewsii	Penstemon digitalis*	Symphyotrichum oblongifolium
Asclepias tuberosa*	Gentianella quinquefolia	Penstemon gracilis*	Symphyotrichum oolentangiense*
Asclepias verticillata*	Glycyrrhiza lepidota*	Penstemon grandiflorus*	Symphyotrichum puniceum*
Astragalus canadensis*	Helenium autumnale*	Penstemon tubaeflorus	Symphyotrichum shortii
Baptisia alba	Helianthus ×laetiflorus	Penthorum sedoides	Tephrosia virginiana
Baptisia australis	Helianthus grosseserratus*	Physocarpus opulifolius*	Thalictrum dasycarpum*
Baptisia bracteata	Helianthus maximiliani*	Physostegia angustifolia	Thaspium trifoliatum
Baptisia sphaerocarpa	Helianthus mollis*	Physostegia virginiana	Tradescantia bracteata
Bidens aristosa*	Helianthus occidentalis*	Polemonium reptans*	Tradescantia ohiensis*
Bidens cernua*	Helianthus pauciflorus*	Polygonatum biflorum	Tradescantia sp.
Blephilia hirsuta	Heliopsis helianthoides*	Polygonum punctatum	Trifolium hybridum*
Boltonia asteroides*	Hibiscus laevis	Polygonum virginianum*	Trifolium pratense*
Boltonia decurrens	Hypericum ascyron*	Potentilla arguta*	Trifolium repens*
Brickellia eupatorioides var. eupatorioi	Hypericum prolificum	Pulsatilla patens ssp. multifida	Triosteum perfoliatum
Callirhoe involucrata	Iliamna rivularis var. rivularis	Pycnanthemum tenuifolium*	Veratrum virginicum
Callirhoe triangulata	Iris versicolor*	Pycnanthemum verticillatum var. pilosum	Verbena hastata*
Camassia scilloides	Iris virginica var. shrevei	Pycnanthemum virginianum*	Verbena stricta*
Campanulastrum americanum*	Lespedeza capitata	Ratibida columnifera*	Verbesina alternifolia
Ceanothus americanus*	Liatris aspera*	Ratibida pinnata*	Vernonia fasciculata*
Chamaecrista fasciculata*	Liatris ligulistylis*	Rosa arkansana*	Vernonia gigantea ssp. gigantea*
Chamerion angustifolium	Liatris punctata*	Rosa blanda*	Veronicastrum virginicum*
Cirsium discolor*	Liatris pycnostachya*	Rudbeckia fulgida	Zizia aptera*
Cirsium hillii	Liatris scariosa	Rudbeckia hirta*	Zizia aurea*
Coreopsis lanceolata*	Liatris spicata	Rudbeckia laciniata*	
Coreopsis palmata*	Linum lewisii	Rudbeckia subtomentosa	
Coreopsis tripteris*	Lobelia cardinalis	Rudbeckia triloba*	

We acquired seed mix information from a combination of vendor websites, downloadable pdf's, and direct communication with vendors. In many cases, vendors were reluctant to share cost details for wildflower seed because the volatility of the seed market and fluctuations in yield and harvest quality from year to year make cost estimates valid in the short term only. We gathered cost data from all vendors within a one month period, so comparisons of the relative costs and benefits of analyzed mixes is informative despite these fluctuations in absolute cost.

Seed vendors use varying nomenclatures and measurement units to provide seed mix information, expressing seeding rates in terms of bulk pounds per acre, PLS pounds per acre or seeds per square foot, expressing mix cost in terms of cost per bulk pound, cost per PLS pound, or cost per acre, and detailing species composition in terms of bulk pounds per acre, PLS pounds per acre or percentage of the full mix by weight or by seeds per square foot. Price lists of individual wildflower and grass species were similarly variable, reporting costs per bulk pound, per PLS pound, or sometimes per oz or packet of seed. In many cases NRCS requires CP42 mixes to meet minimum requirements for live seeds per square foot or for PLS pounds per acre, while vendors sell seed of forb species in terms of bulk pounds. All seed mix composition data were converted to PLS pounds when possible, or else to bulk pounds in order to relate to the relevant vendor's price list and calculate the cost per acre of the full mix and of each species in the mix. Prices per PLS pound of wildflower seed can be an order of magnitude higher than prices per bulk pound from teh same vendor, so mix costs calculated using PLS and bulk pound pricing were analyzed separately.

Similar variation in plant nomenclature was observed between vendors, and between seed mix specifications and price lists, with plants referenced using common names as well as Latin names from different nomenclatures. We standardized all seed mixes, price lists and plant-pollinator interaction data sets using USDA PLANTS nomenclature current as of November 16, 2018.

California

In contrast to Minnesota's 14,599 acres, California had only 1,821 cumulative CRP acres installed with CP42 pollinator plantings as of September 2018. CRP enrollment is low in California because the combination of high land values and low CRP rental payments makes it economically unattractive to take land out of production for the long term (Tom Moore, NRCS CA State Biologist personal communication). Instead NRCS supports pollinators in California through Conservation Cover plantings (NRCS Practice Standard 327) which allow for federal cost share on actively producing lands through the EQIP program.

327A – Conservation Cover, Pollinators

Conservation Practice Specification

(Photo: Jessa Kay Cruz, The Xerces Society)

Specifications

These instructions provide in-depth guidance on how to install wildflower plantings for pollinators and beneficial insects. To plan a specific project, planner will follow these Specifications to fill out the *Implementation Requirements* sheets.

Definition and Purpose

Written Establishing and maintaining permanent cover to enhance habitat for pollinators and beneficial insects

Client Conservation Objectives

Depending on landowner objectives and project design, conservation cover for pollinators also will enhance wildlife habitat, may reduce soil erosion and sedimentation, improve soil, water or air quality, or help manage plant pests by removing weeds that harbor pest insects or by increasing habitat for predaceous and beneficial invertebrates as a component of an integrated pest management plan.

327A-Conservation Cover, Pollinators | Specifications | NRCS, CA | Nov 2017 1

In response to the high cost of native wildflower seed limiting enrollment in 327A, the NRCS and the Xerces Society for Invertebrate Conservation designed a seed mix in collaboration with researchers at UC Davis that met 327A specifications and was believed to be cost effective based on observations of bee use of key wildflower species. NRCS negotiated with seed vendors in 2014 to pre-mix seed and sell the mix at a negotiated rate instead of selling at individual species prices. There are currently two mixes designed for different regions of the state, a Central Valley mix and a Southern Coastal mix.

We interviewed four vendors selling pollinator mixes in California, and received data on the cost and species composition of mixes from two of these (Table X). We evaluated a total of 14 forb-rich mixes in California, with two vendors providing the 327A Central Valley pollinator mix and one selling the 327A Southern CA mix. The remaining eleven mixes were designed by vendors for flowering plant diversity, with just one of these specifically targeting support of pollinators.

These fourteen mixes yielded information on 78 flowering forb and shrub species, 21 of which occur in the plant-pollinator interaction data set provided by collaborators at UC Davis (Table 4). These 21 species with both cost and pollinator-use data comprise more than 75% of the mix-by-species combinations used in the 14 seed mixes analyzed in California.

Table 4. Forbs and flowering woody species included in California 327A Conservation Cover and vendor-designed pollinator and other forb-rich mixes. Species with an asterisk also occurred in the plant-pollinator interaction data, and were included in the optimization modeling. Nomenclature follows USDA PLANTS database standards as of Nov 16, 2018.

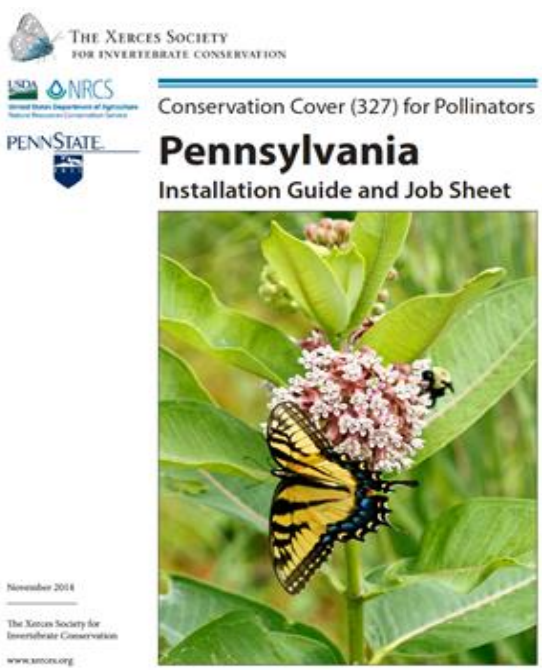
*Achillea millefolium**	*Linum lewisii*
Ambrosia dumosa	*Lobularia maritima*
Artemisia californica	*Lotus corniculatus*
Artemisia tridentata	*Lotus scoparius*
Atriplex canescens	*Lotus unifoliolatus var. unifoliolatus*
Atriplex polycarpa	*Lupinus bicolor*
Calendula officinalis	*Lupinus densiflorus**
*Camissonia cheiranthifolia**	*Lupinus densiflorus var. densiflorus*
Camissonia pallida	*Lupinus nanus*
Centaurea cyanus	*Lupinus sparsiflorus*
Clarkia amoena	*Lupinus succulentus**
Clarkia bottae	*Melilotus indicus*
*Clarkia purpurea**	*Nemophila maculata**
*Clarkia unguiculata**	*Nemophila menziesii**
*Clarkia williamsonii**	*Papaver rhoeas*
Cleome isomeris	*Penstemon spectabilis*
*Collinsia heterophylla**	*Phacelia californica**
Coreopsis lanceolata	*Phacelia campanularia**
Coriandrum sativum	*Phacelia ciliata**
Dianthus barbatus	*Salvia apiana*
Dimorphotheca sinuata	*Salvia columbariae**
Diplacus aurantiacus	*Salvia mellifera*
Diplacus longiflorus	*Silene armeria*
Diplacus puniceus	*Sisyrinchium bellum*
Encelia californica	*Sphaeralcea ambigua**
Encelia farinosa	*Trifolium incarnatum*
Ericameria nauseosa ssp. nauseosa var.	*Trifolium willdenovii*
Eriodictyon crassifolium	
Eriogonum cinereum	
Eriogonum fasciculatum	
Eriophyllum confertiflorum	
Eschscholzia caespitosa	
*Eschscholzia californica**	
Eschscholzia californica ssp. mexicana	
Gaillardia pulchella	
Gazania rigens	
*Gilia capitata**	
Gilia tricolor	
*Grindelia camporum**	
Gypsophila elegans	
*Helianthus annuus**	
*Helianthus bolanderi**	
Hesperoyucca whipplei	
Isocoma menziesii	
Larrea tridentata	
*Lasthenia californica**	
Layia platyglossa	
Linum grandiflorum	

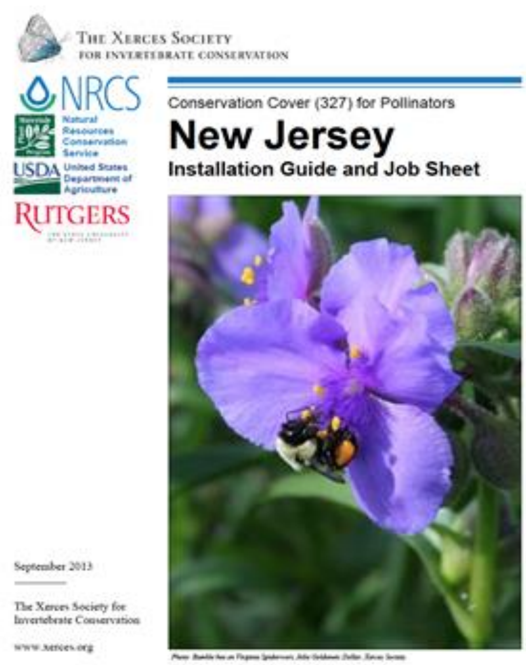
Plant-pollinator interaction data in California were obtained from two studies separate studies. We used data described in Williams and Lonsdorf (2018). In their paper, they state that, “Bee-phenology data were obtained from a regional dataset containing 7610 specimens from Northern California collected at 16 sites over seven sampling rounds spaced evenly between March and late August across habitat types (Williams et al. 2011, Forrest et al. 2015). Bees were netted from flowers, and all plants and bee specimens were identified to species or in a few cases bees to numbered morphospecies (155 specimens in the genera *Lassioglossum* (124) and *Osmia* (2), *Duforea (9), Nomada (6),* and *Hylaeus* (2)). We used the earliest and latest records from our data set to define the adult flight season for that bee species. Plant phenology data were extracted from the Consortium of California Herbarium (http://ucjeps.berkeley.edu/consortium/). We used all records from specimens collected “in flower” at elevations between 0 and 500 m from 21 northern California counties in our region. All species had at least 38 records, and all but three exceeded 50. Our test data set consists of approximately 2348 records of wild bee-native plant interactions. The data are a subset from the larger dataset used to identify bee phenology that included non-native plant interactions as well as trees and the phytotoxic *Toxicodendron diversilobum*. However, because our goal includes a practical application of habitat restoration we excluded these species, which would not be desired nor practical to implement.”

In 2015 Ward and Williams collected data on bee use of 45 California native plant species from replicated single species test plots planted at UC Davis. These include all of the species in the Central Valley Pollinator Conservation Seed Mix and additional species considered promising because of data that show they support bees, they bloom at various times of the season, are adapted to local climate and soils, and are available from native seed producers (Table 2). Test plots were monitored weekly from March 26 through Dec 2m, 2015 for floral resource availability and bee use.

Pennsylvania/New Jersey

Pennsylvania and New Jersey had by far the lowest rates of CP42 installation, with only 10 and 14 cumulative acres respectively, as of September 2018. Like in California, most pollinator plantings are installed through the EQIP program and meet specifications of NRCS Practice Standard 327A -- Conservation Cover. Requirements for 327A in PA and NJ include: 75% or more forbs as measured by seeds/square foot; minimum of three species flowering in each of early, mid and late-season, with a focus on native plant species, although non-invasive nonnatives are allowable when cost or availability are limiting factors.





We interviewed 6 vendors selling forb-rich seed mixes in PA and NJ, with four of these providing data on cost and species composition in sufficient detail for our analyses (Table X). We obtained data on one CP42 mix designed for PA, 8 mixes meeting 327A Conservation Cover specifications (including example mixes provided in the NJ and PA Installation Guides), and 24 vendor-designed mixes with more than half of these being specifically tailored to pollinators.

These 33 mixes provided data on 82 flowering forb and shrub species, 53 of which also occur in the plant-pollinator interaction data set. These 82 species with both cost and pollinator-use data comprise more than 80% of the mix-by-species combinations used in the 33 seed mixes analyzed in New Jersey and Pennsylvania.

Table 5. Forbs and flowering woody species included in Pennsylvania and New Jersey 327A Conservation Cover and vendor-designed pollinator and other forb-rich mixes. Species with an asterisk also occurred in the plant-pollinator interaction data, and were included in the optimization modeling. Nomenclature follows USDA PLANTS database standards as of Nov 16, 2018.

*Achillea millefolium**	*Pycnanthemum tenuifolium**
Achillea millefolium var. occidentalis	*Pycnanthemum virginianum**
*Agastache foeniculum**	*Ratibida columnifera**
Ageratina altissima var. altissima	*Rudbeckia fulgida*
Anemone virginiana	*Rudbeckia fulgida var. fulgida*
*Asclepias incarnata**	*Rudbeckia hirta**
*Asclepias syriaca**	*Senna hebecarpa**
*Asclepias tuberosa**	*Senna marilandica*
Baptisia australis	*Silphium perfoliatum**
Baptisia tinctoria	*Silphium trifoliatum*
*Centaurea cyanus**	*Solidago bicolor*
*Chamaecrista fasciculata**	*Solidago canadensis**
Chrysopsis mariana	*Solidago juncea**
Conoclinium coelestinum	*Solidago nemoralis**
*Consolida ajacis**	*Solidago rugosa**
*Coreopsis lanceolata**	*Solidago sempervirens**
*Coreopsis tinctoria**	*Solidago speciosa**
*Coreopsis tripteris**	*Symphyotrichum laeve**
*Dianthus barbatus**	*Symphyotrichum laeve var. laeve*
*Echinacea purpurea**	*Symphyotrichum lateriflorum**
*Eryngium yuccifolium**	*Symphyotrichum lateriflorum var. lateriflorum*
*Eupatorium perfoliatum**	*Symphyotrichum lowrieanum*
Eurybia divaricata	*Symphyotrichum novae-angliae**
*Euthamia graminifolia**	*Symphyotrichum novi-belgii**
eutrochium fistulosum	*Symphyotrichum oblongifolium*
*Eutrochium maculatum**	*Symphyotrichum prenanthoides*
*Eutrochium purpureum**	*Tradescantia ohiensis**
*Helenium autumnale**	*tradescantia virginiana*
*Helianthus annuus**	*Trifolium incarnatum*
*Helianthus giganteus**	*Verbena hastata**
*Helianthus maximiliani**	*Verbesina alternifolia*
*Heliopsis helianthoides**	*Vernonia noveboracensis**
Hibiscus moscheutos	*Veronicastrum virginicum**
*Iris versicolor**	*Zizia aurea**
Kosteletzkya virginica	
Leucanthemum maximum	
Liatris spicata	
Linum perenne	
*Lobelia siphilitica**	
*Lupinus polyphyllus**	
*Mimulus ringens**	
*Monarda bradburiana**	
*Monarda didyma**	
*Monarda punctata**	
Papaver rhoeas	
*Penstemon digitalis**	
*Penstemon hirsutus**	
Penstemon laevigatus	

Integrating seed mix cost data with plant-pollinator interaction observations

Plants used in the analysis: We used the same process for each region to combine data from seed vendors with the data on pollinators, plants and their interactions. The final plant species included in the genetic algorithm were those that were found in both the plant-pollinator observations and the data seed mix data gathered from various vendors as described above. The plant and bee phenology data, along with the plant-bee interaction data were provided by our collaborators, representing past or ongoing research. In all cases for pollinators, data represent observations of pollinator visits to flowers in which both the bee and flowering plant species could be identified. The date of observation was provided for these data and thus contributed to the bee's foraging phenology, and phenologies were organized by month from the first day to the last day of that month.

Key assumptions of the analysis

There are several data gaps so assumptions were needed to compare vendor data with the analytical approach. These assumptions involve the sets of species included, the inclusion of grass, and how to deal with varying seed density. The biggest challenges we have to address are the range of seeding rate options to allow and the effect of seeding density on pollinators .

- **Seeding rate range:** We allowed the algorithm to choose among 6 options for seeding rate, from 0 to 5 ounces with 1 oz steps. We can use observed seed density rates from surveyed seed mixes to set the options within the model. We found that individual species seeding rates of 5 ounces of live seed or less per acre was used in just under 85% of the 1319 forb species-by-mix combinations, and around 1 oz was by far the most frequent amount of seed used (Figure 3). We used this information to define the seeding rate options available to the algorithm and the assumption about how effective each rate was in providing flowers for bees.

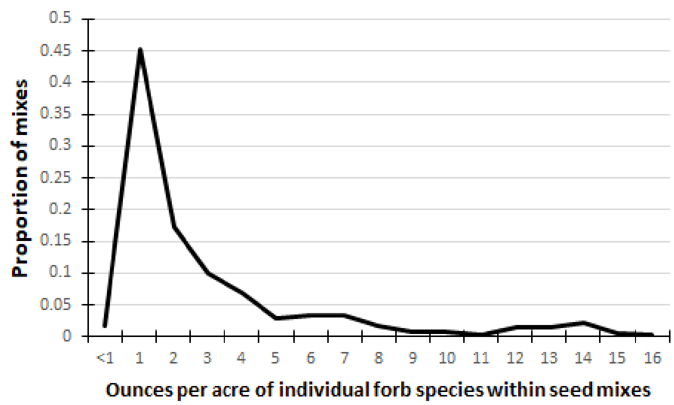


Figure 3. Frequency distribution of the amount of live seed used per acre for individual species included in mixes used in Minnesota, California and Pennsylvania/New Jersey.

- *Effects of seed density on pollinators:* We are unaware of any studies that have evaluated how variation in seeding rates of pollinator plantings affect plant establishment and floral resource provision. In fact, we are both involved in a recently initiated research project to study this experimentally in Minnesota and California. Although we don't know precisely how seed density affects pollinator support, we can make some basic assumptions that attempt to address this. For example, there is likely a range of seed densities for each species in a planting, such that at low densities, increasing density leads to increasing support of pollinators but above a certain threshold, adding more seeds will not increase the support. We assumed that 1 oz of seed per acre would eventually provide floral resources that are 33% as effective at supporting bees as the maximum density of flowers possible and that each additional ounce would add 8.25% more.

This results in a "dose-response" curve as represented below relating seeding rate to a plant species' ability to support a single bee species with enough floral resources. In the model described by Williams and Lonsdorf (2018), each bee species is not supported unless it receives full support over all relevant phenological periods over which that species is active. These two assumptions mean that a mix means that at least two plant species are needed in the optimization to support one or more bee species; if 5 ounces of one species (the maximum allowed in the analysis) is included, it is predicted to provide 67% of the floral resources required for a bee (Figure 4). One ounce of one other species would be needed to increase the total floral support to 100% *and* they would have to cover the relevant phenological periods. While the model analysis restricts seed mixes to having 5 or fewer ounces per species, it is possible for a single plant from the vendor's data to cover a bee on its own because there are a few cases when seeding rate would predict 100% support (i.e. 9 or more ounces per acre).

In making these assumptions, we recognize the challenge of using weight, rather than live seeds, as the unit of the decision variable. Species vary widely in the weight of an individual live seed. In practice, small-seeded species have lower germination and establishment success, and lower competitive ability, on a per-seed basis, than large seeded ones. So although it's not perfect, standardizing among species using weight is a reasonable approximation to correct for this. We also recognize that using the same weight means many more seeds for small-seeded species than large-seeded (which is potential for overcrowding), and also true that one would never plant a single seed per square foot of a poppy (tiny seed) and expect the same establishment as one seed per square foot of lupine (huge seed) because the lupine is more likely to germinate and will be bigger so more likely to establish. But there's no set relationship you could apply across the board to titrate these tendencies perfectly. Ultimately, the relationship we've depicted is based on experience considering seed size, germination timing (early-germinators establish better than late), and other details of the biology of the plant plus a feel for it that one gets from watching the outcome of plantings. Thus we feel that using weight is a reasonable approximation to correct for the lower success per seed of small-seeded species.

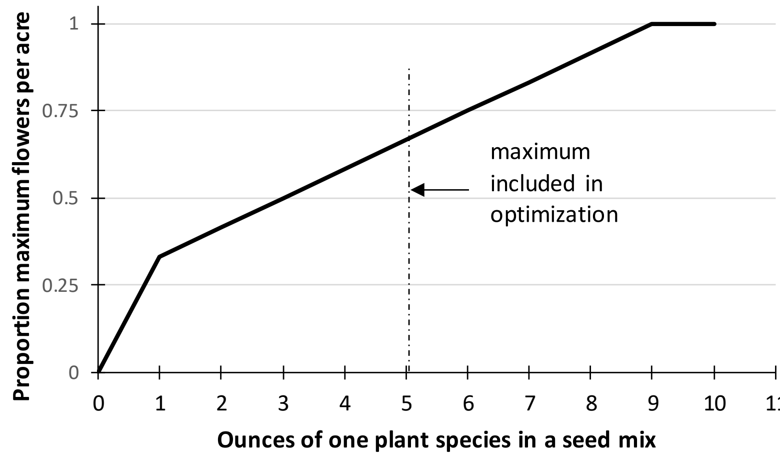


Figure 4. "Dose-response" curve relating the ounces of one plant species in a seed mix to its ability to support bees, as defined the proportion of maximum flowers per acre.

- *Plant species included:* In all regions, there were plants used in the seed mixes for which there were no bee observation data and there were observations of bees using plants that were not included by seed vendors in the mixes. These plants were not included in the genetic algorithm-driven seed mix design. We think that the results are likely robust to this issue as the species included made up at least 80% of the non-grasses used in the mix by weight and most cases over 90%.
- *Excluding grass:* We ignored grass in the analysis, but think that our analysis is robust to this. Grass species are nearly always cheaper than the forbs and their costs typically don't vary as much among species. Cheaper mixes typically have more grasses by weight. Thus the problem to solve is mainly about finding the most cost-effective set of forbs to combine with the grasses.

Methods for analysis (modified slightly from Williams and Lonsdorf 2018)

Our framework for selecting plants is based on an understanding of how a bee species or set of species is supported by a set of planted species throughout an adult flight season. The persistence of any bee species requires that nesting females (or colonies) have access to pollen and nectar resources throughout the adult lifespan. Gaps or curtailment of resources will reduce survival and/ or the number of offspring (Memmott et al. 2007, Russo et al. 2013). At its core, this framework requires four types of data that represent the components of plant-pollinator interactions: 1) the adult phenology of each bee species, which defines the required resource coverage over time; 2) a bee-by-plant visitation matrix, which identifies the set of plant species from which each bee species collects resources; 3) the flowering phenology of those plants, which defines the ability of any plant to meet the phenological coverage needs of bees, as well as its overlap with other such plant species and 4) the expected cost to plant each species. Such data can then be used to compare the costs and benefits of alternative sets of plant species that fully support a bee, or set of bees, defined by the goal of maximizing bee richness supported by the mix for a given budget. The same approach can be generalized to include additional plant or bee traits that might influence selection toward any defined goal (e.g., whether a given plant species is drought tolerant or whether a given bee is a known to pollinate a crop of interest). Our model integrates these data types to predict the bee community supported by the selection of plant species.

First, **B** is a matrix with dimensions, *b* x *T,* defining the observed phenology of the *b* bee species across the *T* time periods, which divide the entire flight season for all bees in the community. The elements of the matrix are 1 if the bee has been observed at a particular time period, or 0 if it is not.

P is a *p* x *T* matrix that represents the ability of planted floral resources to support bees by each of *p* plant species across the *T* time periods. The elements of the matrix are determined by the plant phenology and the effect of the decision of how much to include in the set of planted species. Floral phenology is indicated by each plant species *i* at time *t,* F_{it}, and is equal to 1, if plant species *i* is flowering at a time period *t* or 0, if it is not. The expected floral resources provided over time is determined by F_{it} and the decision variable, x_i, which is an integer from 0 to 5 representing the number of ounces included. The proportion of a bee species supported by plant species *i* flowering at time *t*, P_{it}, is equal to:

$$P_{it} = (ceiling\left(\frac{x_i}{5}\right) * (\frac{1}{3}) + (\frac{2}{3}) * (F_{it} * x_i) - 1)/8.$$

The function, *ceiling*, rounds the calculation up to the nearest integer such that $ceiling\left(\frac{x_i}{5}\right)$ is equal to 0 if x_i is 0, and 1 if x_i ranges from 1 to 5 ounces. Note that the “dose-response” curve above represents the assumptions here.

I is a *b* x *p* matrix that represents the interaction of each bee with each potential plant species, where the elements of the matrix are 1, if the bee has been observed visiting the plant species or 0, if it has not. To predict the expected number of plant species in each time period that could support each of the *b* bee species, the floral resources for bees matrix, **P**, is multiplied by interaction matrix, **I**, and followed by an element by element multiplication of the bee phenology matrix:

$$\widehat{\mathbf{B}} = (\mathbf{I} \times \mathbf{P})^{\circ}\mathbf{B}.$$

The product, ***I****x****P***, produces a *b* by *T* matrix whose elements are integers that represents the total floral support from plant species that a particular bee species can rely on during time period *t*. The Hadamard (element-by-element) product of this matrix with **B** simply screens out those entries when the bee species does not require any plant species. The resulting matrix, $\widehat{\mathbf{B}}$, is thus also a *b* by *T* matrix.

To determine the proportion of the flight season of bee species *j* that is supported by the plants chosen, we compare the flight seasons supported by the mix to the flight seasons the bees require. For example, the plant mix may support three time periods used by a bee, but that bee may require support for four periods. We assumed that as the proportion of the observed bee species’ flight season that is supported by at least one plant species increases, the probability that bee species *j* is supported, b_j, also increases, such that:

$$\beta_j = floor\left(\frac{\sum_{t=1}^{T} min(\hat{B}_{jt},1)B_{jt}}{\sum_{t=1}^{T} B_{jt}}\right),$$

where $\hat{B}_{jt}$ is an element of $\widehat{\mathbf{B}}$ indicating the floral resources supporting bee species *j* at time *t*, and B_{jt} is an element of **B** indicating whether or not bee species *j* needs to be supported at time *t*. In the numerator, we use the minimum of B_{jt} and 1 because we assume that only one plant species is needed to support each bee species during each time period. The denominator represents the total number of time periods used by species *j* and the numerator is thus the number of periods supported by plants chosen. The function, *floor*, rounds the calculation down to the nearest integer such that b_j is equal to 0 if any of the bee's time periods are not covered and 1 if all its time periods are supported.

Solving the problem

The problem to solve can be formulated simply as follows:

$$\text{maximize} \sum \beta_j$$

$$\text{Subject to} \sum x_i \varepsilon_i \leq \kappa \ \& \ 16 \leq \sum x_i \leq 72$$

where x_i, as before, is the decision variable representing the number of ounces of plant species *i* included in the restoration and ε_i is the cost per ounce of each plant species *i*. The left side of the first constraint represents the expected cost of the planting and the right side is the budget, represented by κ. The second constraint illustrates that we constrained the total weight of the forbs in the mix to be between 14 and 72 oz of forb seed per acre (values that capture the majority of the observed mixes).

We used a genetic algorithm (Matlab 2018) to evaluate plant mixes and identify best sets of plant species for a range of budgets. Genetic algorithms are often applied to non-linear problems with many potential decisions like this one. The number of possible solutions is equal to the number of possible planting decisions for each plant species, (6 options ranging from 0 oz/ac to 5 oz per ac), raised to the number of species options. In the Minnesota analysis there are 72 plant species to choose from so there are 6^{72} possible solutions (1.06 x E^{56}). A genetic algorithm is not considered an optimization routine as it applies principles of natural selection as a heuristic to generate as good a solution as possible (Olden et al. 2008). Indeed as we explored the application of the genetic algorithm, we found that the solution varied from run to run and we attribute this to the large size of the problem. To get around this, we ran the genetic algorithm 100 times and chose the resulting mix that supported the greatest number of bee species.

Sensitivity analysis

There are a growing number of studies of plant-pollinator networks that could be leveraged to parameterize the analysis, but not all locations are likely to have robust interaction data. With this in mind, we evaluated the effects of ignoring the interaction data, essentially assuming that all bees could visit all plants if it is flowering when the bees are flying. In other words, let the interaction matrix, ***I***, be equal to 1 for all elements and see what difference it makes. We ran this for Minnesota only.

Additionally, we explored alternative solution mechanisms by using a greedy algorithm, rather than the genetic algorithm. This analysis sought to maximize the increase in the bee species supported per added cost of additional oz. Recall that our original assumptions stated that nine ounces across at least two plant species were needed to provide floral resources *and* all flight phenologies need to be covered to support a bee species. These assumptions mean that no bees could be supported for less than nine ounces. Thus we relaxed these assumptions and allow bees to be partially supported such that bees supported were:

$$\beta_j = \left(\frac{\sum_{t=1}^{T} \hat{B}_{jt} B_{jt}}{\sum_{t=1}^{T} B_{jt}}\right).$$

To run the heuristic, we added an oz of a single plant species to the mix, calculated the new bee species supported and the added cost, and then calculated the marginal gain in species divided by the marginal gain cost. We repeated this for each potential plant species and selected the species that provided the largest gain in bee species relative to added cost. We applied the resulting mixes to the analysis with all original assumptions included.

Results

Our analysis indicated that there is substantial opportunity to improve the ability of mixes to support wild bees at lower costs - we found that one could save from $200 to $900 per acre and still support the same number of bees. We summarize the results for each region (MN, NJ/PA, and CA) by providing the results as a figure relating bees supported as a function of budget with open circles representing results of vendor mixes and a solid line representing the results of the genetic algorithm.

Minnesota: We analyzed 51 mixes from Minnesota where we had reliable costs per pound of live seed. Using the full model with the genetic algorithm, we found that the greatest number of bees supported by mixes available from vendors, 47 bee species, was predicted to cost around $329 per acre whereas our genetic analysis indicated that 49 bee species could be supported by a mix that costs $96 per acre (solid line). The same number of bees could be supported and one could save more than $200 per acre. Or one could support 76 bee species for $333, an additional 29 bees for nearly the same price.

We used the optimization approach without interaction data and then applied the results to prediction that includes the interaction to ask: how good is our prediction if we ignore interaction information? The answer is, not very good – basically it's about the same as not using the algorithm at all (dashed lines). We think this result suggests that interaction information is potentially quite valuable as the cost-effectiveness is reduced compared to a solution generated with the information.

The greedy algorithm is better than the analysis without including interactions but not quite as good as a genetic algorithm (grey, solid line). The greedy approach is a bit cumbersome to do given the assumptions we needed to relax to make this assessment work with our data.

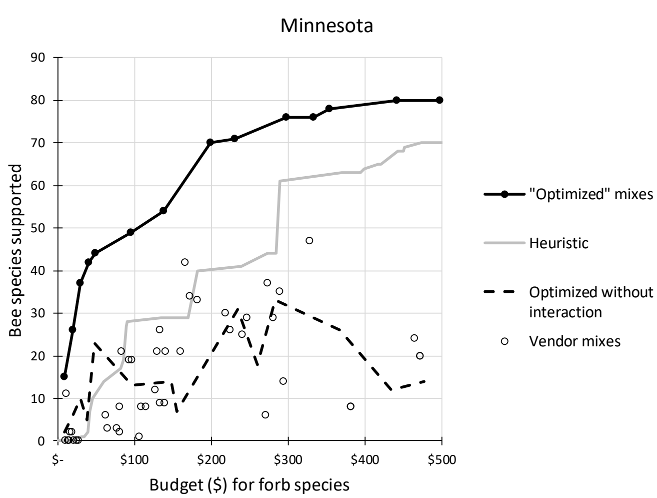


Figure 5. Minnesota cost-benefit analysis.

Pennsylvania/New Jersey: We analyzed 33 mixes from vendors in New Jersey. We found that the greatest number of bees supported by these mixes, 54 bee species, was predicted to cost around $1440 per acre whereas our genetic analysis indicated that 57 bee species could be supported by mix that cost just under $300 per acre. The same number of bees could be supported for nearly $1100 less per acre. Or one could support around 84 bee species for $636, an additional 27 bees and still save around $800 for every acre of planting.

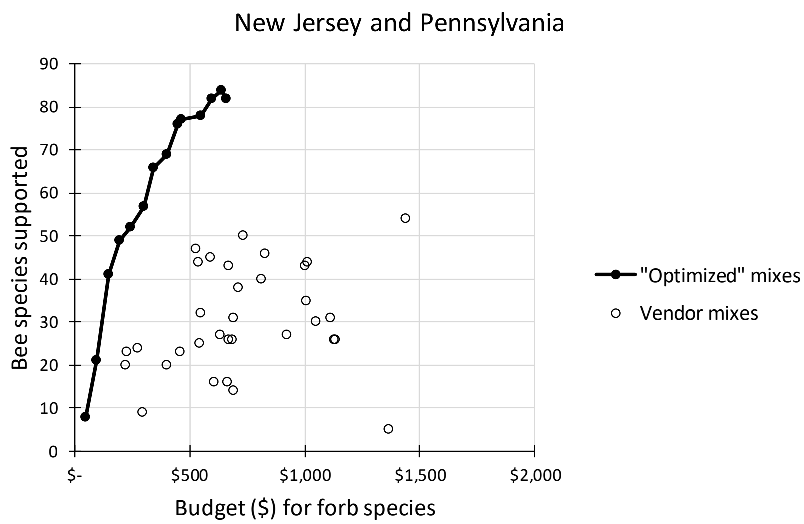


Figure 6. New Jersey and Pennsylvania cost-benefit analysis.

California: We analyzed 14 mixes from vendors in California. We found that the greatest number of bees supported by these mixes, 37 bee species, was predicted to cost around $342 per acre whereas our analysis with the genetic algorithm indicated that 36 bee species could be supported by mix that cost just under $50 per acre. Nearly the same number of bees could be supported for around $300 less per acre. Or one could support 56 bee species for $231, an additional 20 bees and save over $100 per acre.

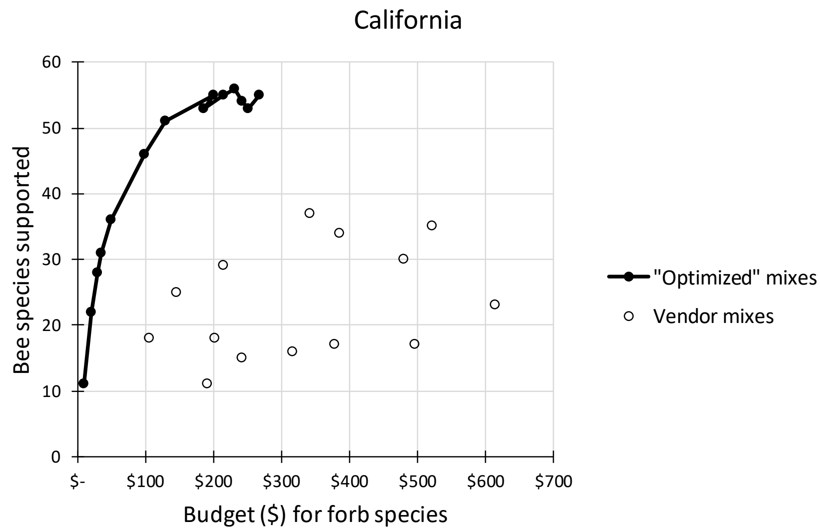


Figure 7. California cost-benefit analysis.

Discussion

Our results clearly suggest that thoughtful seed mix design that takes into account the increasingly available knowledge of plant pollinator interactions in addition to plant costs could lead to mix designs that support pollinators for greatly reduced costs per acre. In other words, pollinators can be supported for lower costs. When considering only the support of pollinators, we found that one could save from $200 to $900 per acre and still support the same number of bees.

The precise results should be taken with a fair bit of caution due to the assumptions we've had to make about the relationship between plant seeding density and floral support for bees. Ongoing work should start addressing this relationship. Also, we are not considering labor costs which are likely more independent of seed costs. Despite these caveats, the results strongly suggest that thinking carefully about plant traits, the functions they are meant to support, and plant costs would allow one to be far more efficient with mix design.

Our results also clearly show the value of including plant-bee interaction data in the analysis. Simply using overlapping floral phenology with bee flight phenology did not produce mixes that were very cost-effective. Thus an analysis that solely looked to create flowering plants throughout the full growing season does not, on its own, suggest constancy of resources to support bees. If plant-pollinator interactions are not readily known, one could attempt to analyze available plant-bee interaction data to determine how associations between bee traits and phylogeny with plant traits and phylogeny, which are widely available, could be used to fill in data gaps making informed *a priori* assumptions about the likely interactions (Hipp et al. 2015).

Overall, we think it would be useful to support standardization of existing plant-bee interaction data like the work we've done. We are aware of other available data from the Great Plains and likely other areas of the US that could be put together to address this question. No doubt this kind of work could also link to a desired National Bee Monitoring Program such that records specifically include the flowering plant species visited along with bee observations.

We focused on the bee community, but similar approaches could be taken for different or complementary objectives. For example, one could be interested in supporting specific pollinators rather than the entire community so the species mix could be modified with that in mind. Alternatively, one could include additional objectives and/or constraints to design the mix. For example, species could be selected to improve soil retention through rapid establishment, provide forage for birds, as well as support pollinators at the lowest cost possible. The analytical approach we used could be applied as long as plant traits are known so that one could evaluate the benefits of the mix as a function of cost.

Acknowledgements
All photos were taken by Kimiora Ward. Thanks to the Cariveau Bee Lab at the University of Minnesota for sharing its extensive plant-pollinator interaction data.

Literature Cited

Forrest, J. R. K., R. W. Thorp, C. Kremen, and N. M. Williams. 2015. Contrasting patterns in species and functional-trait diversity of bees in an agricultural landscape. Journal of Applied Ecology 52:706-715.

Harmon-Threatt, A. N., and S. D. Hendrix. 2015. Prairie restorations and bees: The potential ability of seed mixes to foster native bee communities. Basic and Applied Ecology 16:64-72.

Hipp, A. L., D. J. Larkin, R. S. Barak, M. L. Bowles, M. W. Cadotte, S. K. Jacobi, E. Lonsdorf, B. C. Scharenbroch, E. Williams, and E. Weiher. 2015. Phylogeny in the Service of Ecological Restoration. American Journal of Botany 102:647–648.

M'Gonigle, L. K., L. C. Ponisio, K. Cutler, and C. Kremen. 2015. Habitat restoration promotes pollinator persistence and colonization in intensively managed agriculture. Ecological Applications 25:1557-1565.

MATLAB. 2018a. MATLAB 8.6. The Mathworks Inc., Natick, MA.

Olden, J. D., J. J. Lawler, and N. L. Poff. 2008. Machine learning methods without tears: a primer for ecologists. The Quarterly Review of Biology 83:171-193.

Otto, C.R.V., S. O'Dell, R.B. Bryant, N.H. Euliss, Jr., R.M. Bush and M.D. Smart. 2017. Using publicly available data to quantify plant-pollinator interactions and evaluate conservation seeding mixes in the Northern Great Plains. Environmental Entomology 0:1-14.

Pollinator Health Task Force. 2015. National Strategy to promote the health of honey bees and other pollinators. White House Office of the President, USA.

Williams, N. M., and E. V. Lonsdorf. 2018. Selecting cost-effective plant mixes to support pollinators. Biological Conservation 217:195–202.

Williams, N. M., D. Cariveau, R. Winfree, and C. Kremen. 2011. Bees in disturbed habitats use, but do not prefer, alien plants. Basic and Applied Ecology 12:332-341.