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Research

Using Publicly Available Data to Quantify Plant–Pollinator Interactions and Evaluate Conservation Seeding Mixes in the Northern Great Plains

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Abstract

Concern over declining pollinators has led to multiple conservation initiatives for improving forage for bees in agroecosystems. Using data available through the Pollinator Library (npwrc.usgs.gov/pollinator/), we summarize plant–pollinator interaction data collected from 2012–2015 on lands managed by the U.S. Fish and Wildlife Service and private lands enrolled in U.S. Department of Agriculture conservation programs in eastern North Dakota (ND). Furthermore, we demonstrate how plant–pollinator interaction data from the Pollinator Library and seed cost information can be used to evaluate hypothetical seeding mixes for pollinator habitat enhancements. We summarize records of 314 wild bee and 849 honey bee (*Apis mellifera* L.) interactions detected on 63 different plant species. The wild bee observations consisted of 46 species, 15 genera, and 5 families. Over 54% of all wild bee observations were represented by three genera-*Bombus*, *Lassioglossum*, and *Melissodes*. The most commonly visited forbs by wild bees were *Monarda fistulosa*, *Sonchus arvensis*, and *Zizia aurea*. The most commonly visited forbs by *A. mellifera* were *Cirsium arvense*, *Melilotus officinalis*, and *Medicago sativa*. Among all interactions, 13% of *A. mellifera* and 77% of wild bee observations were made on plants native to ND. Our seed mix evaluation shows that mixes may often need to be tailored to meet the unique needs of wild bees and managed honey bees in agricultural landscapes. Our evaluation also demonstrates the importance of incorporating both biologic and economic information when attempting to design cost-effective seeding mixes for supporting pollinators in a critically important part of the United States.

Key words: native bee, honey bee, forage, plant visit, seed mix

Wild bees and managed honey bees (*Apis mellifera* L.) are critical components of natural and agricultural systems; pollinating a variety of agricultural crops and wildflowers, and contributing to the foundation of terrestrial food webs. Over 85% of all angiosperms require, or benefit from, animal pollination services for sexual reproduction (Ollerton et al. 2011). The value of insect pollination services to agricultural crops is US$15–29 billion annually, and much of this service is attributed to bees (Calderone 2012). In spite of the well-measured contribution of bees to crop pollination and ecosystem function, populations of both wild bees and managed honey bees are declining globally (Aizen and Harder 2009, Burkle et al. 2013). For example, recent research showed that modeled wild bee abundance declined across 23% of the US land area between 2008 and 2013 (Koh et al. 2016). Several wild species in the United States have undergone significant population declines and range contractions (Cameron et al. 2011, Burkle et al. 2013), and *Bombus affinis* (Cresson) has recently been proposed for listing under the US Endangered Species Act. Concurrent with wild bee declines, the number of managed honey bee colonies in the United States has declined steadily since the 1950s (vanEngelsdorp and Meixner 2010), and annual colony losses were estimated at 34% in 2014 (Lee et al. 2015). Current evidence suggests that declines in wild and managed bees can be attributed to a myriad of interacting factors including habitat loss, pesticide exposure, parasites, diseases, and forage availability (Goulson et al. 2015).

Growing societal concern over large-scale pollinator declines has led to a greater emphasis on pollinator conservation efforts across all branches of government and the private sector. In 2015, the US Pollinator Health Task Force (2015) developed a federal strategy for improving honey bees and wild pollinator health, and bolstering monarch butterfly populations. Furthermore, the US Department of Agriculture recently unveiled multiple initiatives to enhance pollinator forage on privately owned lands in the Upper Midwest and Northern Great Plains (NGP). Additionally, private companies and nongovernment organizations have developed partnerships for improving pollinator habitat in agricultural landscapes and urban areas in the NGP. Focusing pollinator conservation efforts in the NGP is in part owing to recent land-use changes (Wright and Wimberly 2013, Johnston 2014, Otto et al. 2016), and the importance of this region to commercial honey bee colonies (Gallant et al. 2014, Smart et al. 2016a), wild pollinator communities (Koh et al. 2016), and monarch butterfly migration (Pleasants and Oberhauser 2013). These private land programs, coupled with pollinator conservation initiatives on federally owned lands, highlight a concerted effort across government to improve habitat for pollinators, particularly in the NGP.

One of the key goals proposed by the Pollinator Health Task Force (2015) is the establishment or enhancement of 7 million acres of pollinator habitat in the United States by 2020. The Task Force also identified several research and monitoring objectives, including improved distributional mapping and quantification of habitat and resource needs of pollinators in the United States. Currently, baseline distribution data and forage ecology studies of wild pollinators are lacking in many regions of the United States. Additional research is needed to improve national pollinator conservation efforts. The Task Force also called for a renewed focus on private and public land partnerships to combat habitat loss for pollinators. In some parts of the NGP, public lands managed by the US Fish and Wildlife Service (USFWS), and private lands enrolled in USDA conservation programs represent some of the few remaining forage lands for wild and managed pollinators. Both of these agencies play an active role in establishing habitat and forage lands for managed honey bees and wild pollinators in the NGP. Although the NGP is a focal area for pollinator conservation efforts, very little research has been done to assess the role of public and private lands in providing forage for pollinators in this region. Evaluation of these lands can greatly improve current management in the NGP, including prairie restorations, land retirement programs, and working land programs; many of which have a strong emphasis on improving forage for pollinators. Lastly, the Task Force also highlighted the need for decision support tools to assist natural resource managers, policy advisors, and ecologists with conservation planning. Ideally, these tools should provide information to users in regions where conservation efforts are either in the early planning stages or ongoing, and should also improve the cost-effectiveness and conservation delivery of habitat enhancements for pollinators.

Here, we highlight the utility of the US Geological Survey Pollinator Library (npwrc.usgs.gov/pollinator/, accessed 19 October 2016), a decision-support tool for understanding plant–pollinator interactions and bee floral resource use. We downloaded data available through the Pollinator Library to summarize plant–pollinator interaction data collected from 2012–2015 on public lands managed by the USFWS, or private lands enrolled in USDA conservation programs in eastern North Dakota (ND). Specifically, we 1) provide a baseline inventory of plant–pollinator interactions for wild bees and honey bees observed on USFWS-National Wildlife Refuges (NWR), USFWS-Waterfowl Production Areas (WPA), and private lands enrolled in the USDA-Conservation Reserve Program (CRP) and USDA-Environmental Quality Incentives Program (EQIP) in eastern ND, and 2) demonstrate how plant–pollinator interaction data can be used to inform conservation seed mix design for wild bees and managed honey bees. This research is timely given the significant interest in promoting and establishing habitat for pollinators on public and private lands in the NGP.

Materials and Methods

In this article, we highlight how users can download data from the Pollinator Library to better understand plant–pollinator communities and evaluate conservation seeding mixes. The Pollinator Library (http://www.npwrc.usgs.gov/pollinator/) offers the users free access to recorded observations of plant–pollinator interactions in the United States. Data published on the Pollinator Library are the result of contributions by scientists studying plant–pollinator interactions. The Pollinator Library offers supplementary information for every plant–pollinator observation, including land-use, date, time, weather conditions, georeferenced coordinates, and other environmental data recorded at the point of observation. To represent how users can access and use data from the Pollinator Library, we downloaded all of the plant–pollinator interaction records available on the website for North Dakota. All of the contributed records for North Dakota were collected as a part of a large-scale project investigating the role of public and private lands in providing forage for pollinators in agricultural landscapes. This project consisted of three field studies led by USGS scientists (N. Euliss, C. Otto, and M. Smart principal investigators) from 2012–2015. All plant–pollinator observations from these studies were made on public lands managed by USFWS or private lands enrolled in CRP or EQIP. Additional details for each field study can be found in Supp. Material 1 (online only) and the plant–pollinator interaction survey methods are described below. We pooled data from these field studies because they 1) had similar research objectives, 2) employed nearly identical methods for documenting plant–pollinator interactions, and 3) uploaded the observation records to the Pollinator Library, thereby making the data publically available.

Plant–Pollinator Interaction Surveys

Plant–pollinator interaction data were collected along transects that were 2 m in width and 20–25 m in length. All transects were conducted in randomly selected locations on public and private conservation fields in eastern North Dakota. Along each transect, bee sampling was conducted using one of two basic sampling methods: 1) Aerial nets were used to capture wild bees visiting flowers during timed searches (5–6 min), and 2) visual observations were used to record flower visits by *A. mellifera*. Wild bees were captured if they were observed on a flower, presumably collecting pollen or nectar. Honey bees were not captured, but flower visits were recorded if the bee was observed visiting a flower. Additional details on wild bee aerial netting can be found in Bryant (2015). Wild bee specimens were kept in individual labeled jars. All relevant field data were recorded on a separate field datasheet including time of capture, date, location, geo-coordinates, observer, and weather. The corresponding plant was identified in the field or a physical plant specimen was brought back to the laboratory for species-level identification. In either case, the individual plant–pollinator observation was clearly recorded at the time of capture.

Wild bee specimens were identified at Northern Prairie Wildlife Research Center (NPWRC) by S. O'Dell and R. Bryant with multiple, dichotomous keys (Michener et al. 1994, Michener 2007, Ascher and Pickering 2016). Physical voucher specimens for all wild bee observations are housed at NPWRC. No *A. mellifera* voucher specimens were collected. Plant–pollinator interaction data were entered on an electronic spreadsheet and uploaded to the Pollinator Library website from May 2015 until October 2016. Although the Pollinator Library provides flexibility in what data attributes are required when submitting plant–pollinator observations, ideally the submitted records are geo-

Table 1. Summary of land use types and bee observation data downloaded from the Pollinator Library (http://www.npwrc.usgs.gov/pollinator/), accessed on 19 October 2016

Land use type	No. of bee observations	Administrating agency
Conservation Reserve Program[a]	476	US Department of Agriculture-Farm Service Agency
Environmental Quality Incentives Program[b]	57	US Department of Agriculture-Natural Resources Conservation Service
National Wildlife Refuge or National Game Preserve[c]	557	US Fish and Wildlife Service
Waterfowl Production Area[d]	73	US Fish and Wildlife Service

[a] http://www.fsa.usda.gov/programs-and-services/conservation-programs/conservation-reserve-program/index (accessed on 19 October 2016).
[b] http://www.nrcs.usda.gov/wps/portal/nrcs/main/national/programs/financial/eqip/ (accessed on 19 October 2016).
[c] https://www.fws.gov/refuges/ (accessed on 19 October 2016).
[d] https://www.fws.gov/Refuges///whm/wpa.html (accessed on 19 October 2016).

referenced, with specific temporal and environmental information (see http://www.npwrc.usgs.gov/pollinator/Downloads). All geographic coordinates pertaining to bee–plant observations were rounded to two decimal places, prior to submission to the Pollinator Library to protect proprietary information, such as location of specific private lands supporting specific bees or visited plants.

Obtaining Interaction Data From the Pollinator Library

On 19 October 2016, we downloaded all plant–pollinator interaction data for North Dakota from the Pollinator Library, which effectively simulates how a user would obtain data from the website. Although the Pollinator Library contains data for a variety of non-pollinating insects, we selected records for just wild bees (i.e. non-*Apis*) or honey bees (i.e., *Apis mellifera*). Similarly, the Pollinator Library presents data from a variety of land-use types, but we chose to focus our analysis on plant–pollinator observations collected on USFWS lands and privately owned lands enrolled in USDA conservation programs (Table 1). To download data, we performed a queried search for all records in "North Dakota" and the following land-use types: "Conservation Reserve Program," "Environmental Quality Incentives Program," "National Game Preserve," "National Wildlife Refuge," and "Waterfowl Production Area." We further subdivided the data by focusing on records of true bees within Hymenoptera. This process yielded 1,163 plant–pollinator interactions-849 *A. mellifera* and 314 wild bee observations (Figure 1). The data we downloaded from the Pollinator Library included bee observations made on Arrowwood National Wildlife Refuge, Sully's Hill National Game Preserve, several Waterfowl Production Areas (WPA), and private lands enrolled in either CRP or EQIP.

Data Analysis

We used the Bipartite package (Dormann et al. 2009) in R (R Core Team 2014) to construct plant–pollinator interaction networks for each land-use category. We used the USDA PLANTS database (http://plants.usda.gov/) to determine indigenous status of all forb species. We provide descriptive statistics to summarize plant–pollinator interactions and forb use, but avoid gratuitous use of null hypothesis testing.

Evaluating Hypothetical Seed Mixes

We demonstrate the utility of plant–pollinator interaction data for the purpose of evaluating hypothetical seeding mixes for pollinator habitat enhancements. We collected seed cost and availability information of all early-, mid-, and late season plants based on our initial search of the Pollinator Library (see Methods: Obtaining Interaction Data from the Pollinator Library) from four seed vendors operating in the NGP. Seed vendors were contacted in July 2016; hence, prices are reflective of the seed market and availability at that time. Seed vendors did not provide a price if the species was unavailable. For each available species, vendors provided the price (USD) of pure live seed (PLS) per pound, and we calculated an average cost for each species among all vendors. We developed three different seed mixes (described below) to represent varying land-management objectives that landowners may consider when enrolling in a land conservation program. Given that North Dakota is 90% privately owned, it is critically important to evaluate conservation seeding mixes that are representative of private lands programs, such as those administered by USDA. For all mixes, we assumed a seeding rate of 40 seeds per ft^2 (430 seeds per m^2; The Xerces Society 2011); 30 forb and 10 grass seeds per ft^2. We included three native grass species in each mix at equal seeding rate so that our seeding specifications were comparable with actual mixes used in our region (Supp. Material 2 [online only]). Hereafter, we refer to the seeding mix based on the number of forbs species included in each mix, rather than grass and forb species combined. For all seeding mixes, we did not consider plant species that were listed as a ND noxious weed for potential inclusion in a seeding mix (Lym 2014). However, we did consider nonnative plants for some of the mixes, as multiple conservation programs in the NGP allow the inclusion of nonnative species in seeding mixes. Mixes were designed using a seed mix calculator developed by Pheasants Forever (http://nebraskapf.com/store/build-your-own-seed-mix/, accessed 12 February 2017) that allows the user to determine seeds per ft^2 being planned and subsequent cost associated with planned rates. Seeds per ft^2 is calculated as PLS pounds per acre multiplied by the PLS per ft^2 at 1 pound per acre. The PLS seeds per ft^2 at 1 pound per acre is calculated as the number of seeds for a species per PLS pound divided by 43,560; the number of ft^2 in an acre. The number of seeds per pound of PLS for a species was obtained from the USDA Plants Database (plants.usda.gov) or from seed vendors if unavailable through USDA. A list of the specific plants, seed cost, and seeding rates information we used for these hypothetical seeding mixes can be found in Supp. Material 2 (online only).

For the first mix (hereafter, "3-species mix"), we considered seed cost as the top priority. Our goal was to keep the seed mix cost at <US$40 per acre (US$99 per hectare). Cost of seed is often a primary concern for landowners in the NGP who may enroll large tracts of land (>30 ha) in a USDA conservation program. Thus, our 3-species mix is representative of multiple grassland conservation programs implemented in this region that may establish perennial cover, but have limited forb diversity and where pollinator forage is not a primary goal. For the 3-species mix, we selected the three cheapest forb species, with at least one bee visit based on our queried search of the Pollinator Library.

We designed the second mix (hereafter, "9-species mix") so that it would be comparable with a CRP-CP42 pollinator planting (https://www.fsa.usda.gov/Internet/FSA_File/cp42_habitat.pdf, accessed 12

Table 2. Summary of plant–pollinator interaction data obtained from the Pollinator Library

Plant family	Plant species	Bee families	Bee genera	No. of bee observations
Apiaceae	*Zizia aurea*	3	5	22
Apocynaceae	*Apocynum androsaemifolium*	1	1	1
	Apocynum cannabinum	2	2	4
Asclepiadaceae	*Asclepias ovalifolia*	1	1	1
	Asclepias speciosa	2	3	6
	Asclepias syriaca	2	2	44
Asteraceae	*Achillea millefolium*	2	4	5
	Cirsium arvense	3	5	290
	Cirsium flodmanii	2	2	4
	Cirsium undulatum	1	2	4
	Cirsium vulgare	1	1	2
	Echinacea angustifolia	2	2	2
	Erigeron annuus	1	2	3
	Gaillardia aristata	1	2	2
	Grindelia squarrosa	2	2	3
	Helianthus maximiliani	1	1	3
	Helianthus pauciflorus	4	4	9
	Heterotheca villosa	1	1	1
	Lactuca tatarica	3	5	9
	Liatris ligulistylis	1	1	2
	Lygodesmia juncea	3	3	3
	Oligoneuron rigidum	1	1	15
	Ratibida columnifera	1	1	2
	Rudbeckia hirta	2	3	15
	Solidago canadensis	3	4	7
	Solidago missouriensis	3	3	5
	Sonchus arvensis	3	8	77
	Taraxacum officinale	2	2	4
	Tragopogon dubius	2	3	4
Brassicaceae	*Berteroa incana*	2	3	4
	Brassica juncea	1	1	3
	Descurainia sophia	1	1	1
	Erysimum asperum	2	3	3
Campanulaceae	*Campanula rotundifolia*	1	2	2
Caprifoliaceae	*Symphoricarpos occidentalis*	1	1	3
Convolvulaceae	*Calystegia sepium*	2	3	3
	Convolvulus arvensis	2	2	4
Elaeagnaceae	*Elaeagnus angustifolia*	1	1	1
	Elaeagnus commutata	2	2	8
Euphorbiaceae	*Euphorbia esula*	1	2	2
Fabaceae	*Amorpha canescens*	3	5	16
	Astragalus bisulcatus	3	3	4
	Astragalus canadensis	1	1	2
	Chamaecrista fasciculata	1	1	1
	Dalea candida	2	2	2
	Dalea purpurea	1	2	18
	Medicago sativa	4	5	163
	Melilotus officinalis	3	6	253
	Trifolium incarnatum	1	1	2
	Trifolium repens	1	1	1
	Vicia americana	1	1	2
Hydrophyllaceae	*Phacelia tanacetifolia*	1	1	1
Lamiaceae	*Monarda fistulosa*	4	8	68
Liliaceae	*Zigadenus elegans*	2	2	4
Linaceae	*Linum lewisii*	1	1	1
Poaceae	*Bromus inermis*	1	1	1
Ranunculaceae	*Anemone canadensis*	3	3	5
Rosaceae	*Potentilla arguta*	4	5	10
	Rosa arkansana	4	5	13
	Spiraea alba	3	4	8
Rubiaceae	*Galium boreale*	2	2	2
Scrophulariaceae	*Penstemon grandifloris*	1	1	1
Verbenaceae	*Verbena hastata*	2	2	2

Number of unique bee families, genera, and total number of plant–pollinator observations are reported. See Supp. Table 3 (online only) for bee species-level data.

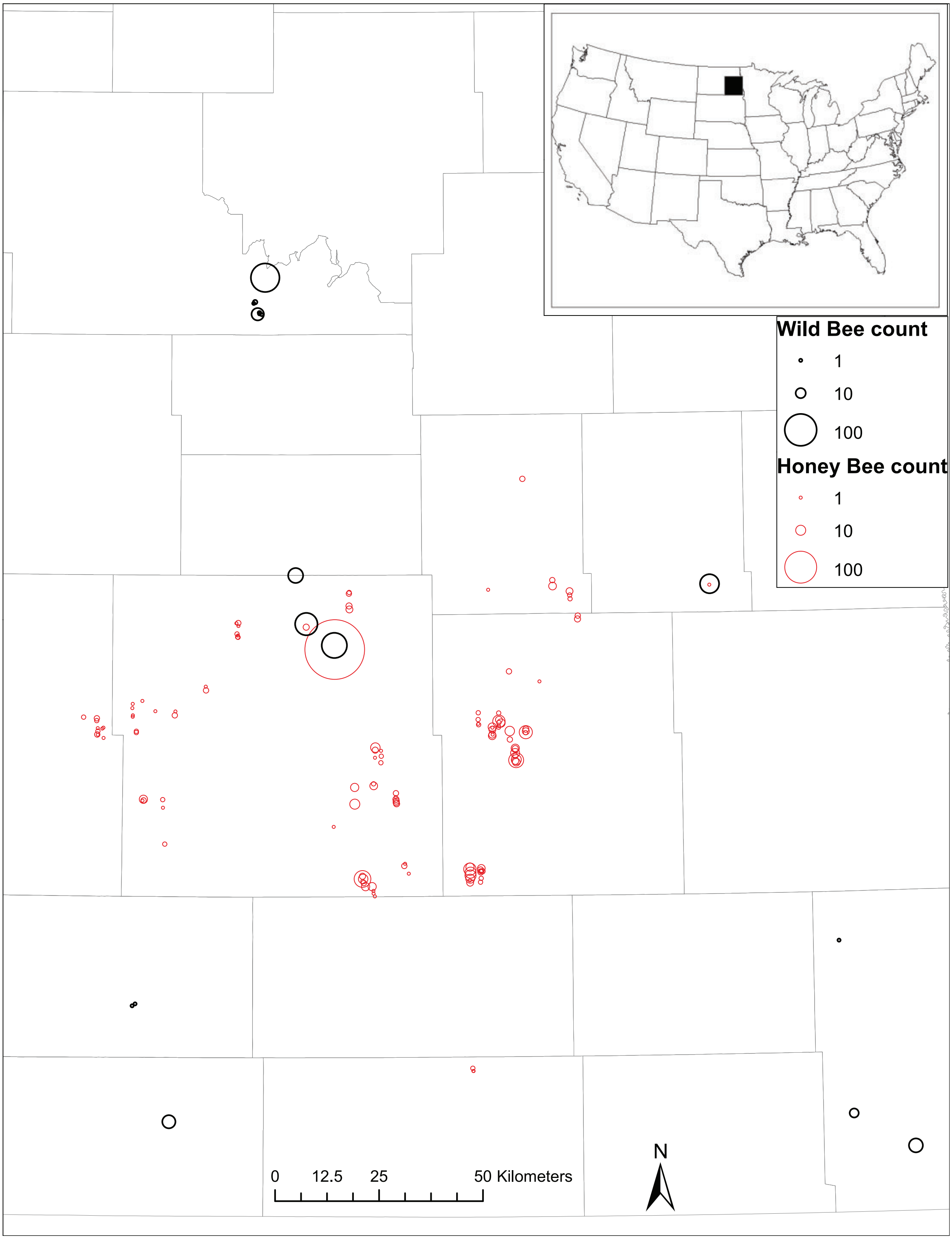

Fig. 1. Map depicting 2012–2015 plant–pollinator interaction records obtained from the USGS Pollinator Library. Red-*A. mellifera*, black-wild bee. Size of the circle corresponds to the number of interaction records obtained for that particular location. (Online figure in color.)

February 2017); nine native or nonnative forb species split among the three bloom periods (i.e., early-, mid-, and late season). Here, bloom period, seed cost, and potential pollinator value were weighted as equal priorities. To develop a candidate list of potential forbs to include in the 9-species mix, we first selected forb species with known bee visits based on our queried search of the Pollinator Library. Whenever possible, we selected plant species with >5 bee visits in the Pollinator Library; however, this generated too few early- and late

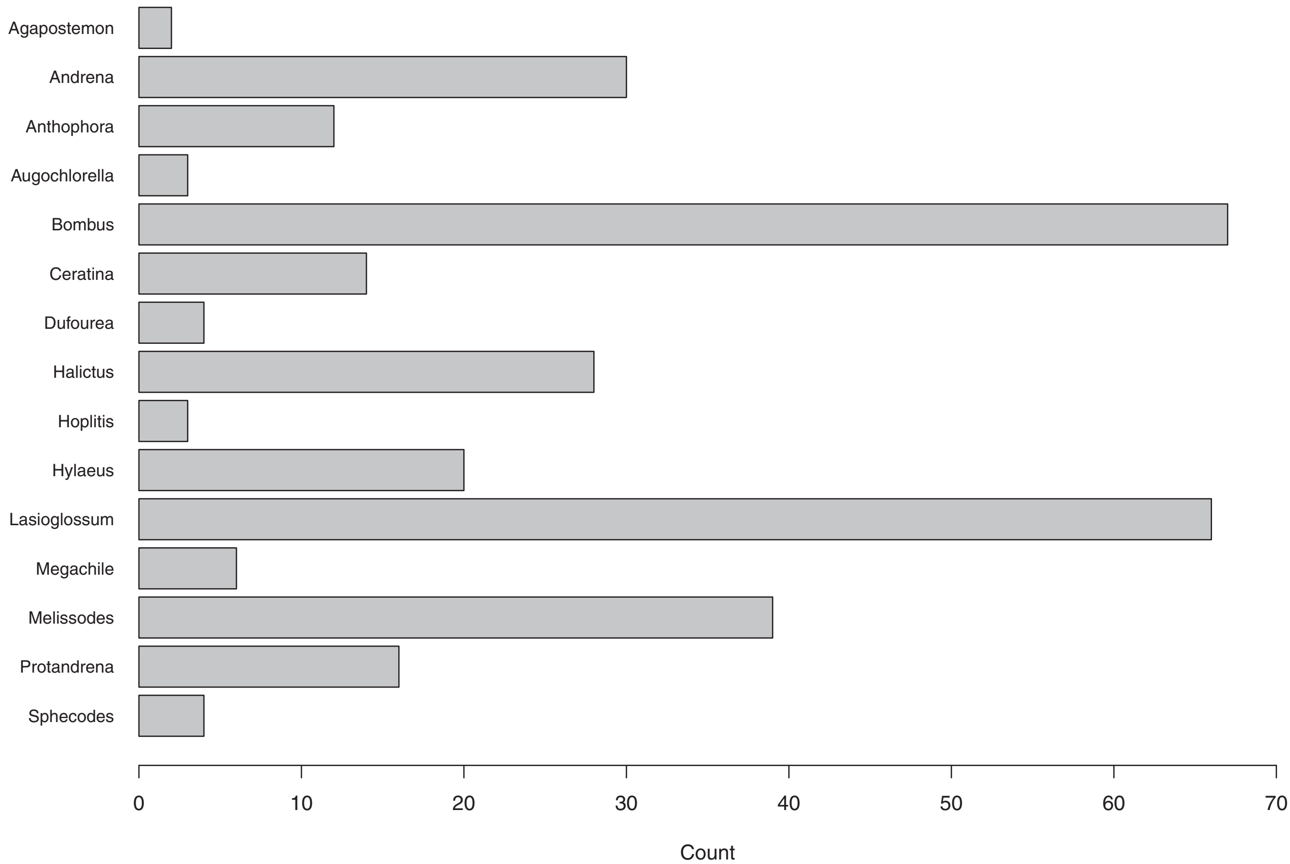

Fig. 2. Bar plot of wild bee genera observations in eastern North Dakota.

blooming species. To fill gaps in the early- and late-bloom windows, we selected two species with <5 visits; *Gaillardia aristata* and *Liatris ligulistylis*. To reduce cost, we included *Medicago sativa* and *Astragalus canadensis* in the 9-species mix because they were relatively inexpensive and are known forage plants for bees (Smart et al. 2017).

For the third mix (hereafter, "26-species mix"), we considered forb diversity, plant indigenous status, pollinator value, and bloom period as the top priorities, without considering seed cost. Given the limited availability of seed for several of the plant species we initially selected, we had to tailor the 26-species mix to include seed that was commercially available by vendors, even if the plant did not represent a sizeable proportion of bee observations in the Pollinator Library. The problem we encountered with limited seed availability of certain species is likely to be a problem for landowners and land managers who purchase seed for conservation plantings. Therefore, our design of seeding mix specifications provides a realistic depiction of the challenges faced in conservation planning and how high-diversity plantings can be heavily influenced by seed availability from regional vendors. For the 26-species mix, we first considered only native plants that held at least one record in the Pollinator Library. From this candidate list, we selected three species of early-, mid-, and late season forbs. For the remaining 17 species, we included early-and mid-season native plants with the highest number of wild bee records from the Pollinator Library.

To evaluate each hypothetical seed mix, we matched plant–pollinator observations from the Pollinator Library with plant species included in each seed mix. Specifically, we matched plant species included in each hypothetical seed mix with the 1,163 plant–pollinator interaction records obtained from the Pollinator Library using the search criteria described above. Our queried search of the Pollinator Library allowed us to quantify the number of unique bee families, genera, species, and total number of bee observations for plant species included in each mix. When tabulating the number of bee species represented by each seed mix, we did not count insect records that were not identified to the species level (i.e., we removed all records ending in "sp."). This provided a conservative estimate of the number of bee species associated with each seed mix. We compared the number of wild bee and honey bee observations queried from the Pollinator Library for each mix, with the total number of wild bee and honey bee observations available on the Pollinator Library for our target land-use types in eastern North Dakota (i.e., 849 honey bee and 314 wild bee observations). This allowed us to calculate the percent of bee interactions that would be represented in each mix, relative to the total number of interactions available on the Pollinator Library. In addition, for each seeding mix, we generated accumulation curves for wild bee and honey bee observations based on our queried search from the Pollinator Library and plant species included in each mix. By summarizing existing Pollinator Library data, our evaluation did not allow us to directly predict which bee species would use each seeding mix, or determine bee preference of specific plants. Rather, using publically available data from the Pollinator Library allowed us to assess economic and biologic tradeoffs associated with the alternative mixes in a framework that will be useful for natural resource managers.

Results

Bee Observations

Our queried search of the Pollinator Library generated 314 wild bee (i.e., non-*Apis*) and 849 honey bee (*A. mellifera*) and plant

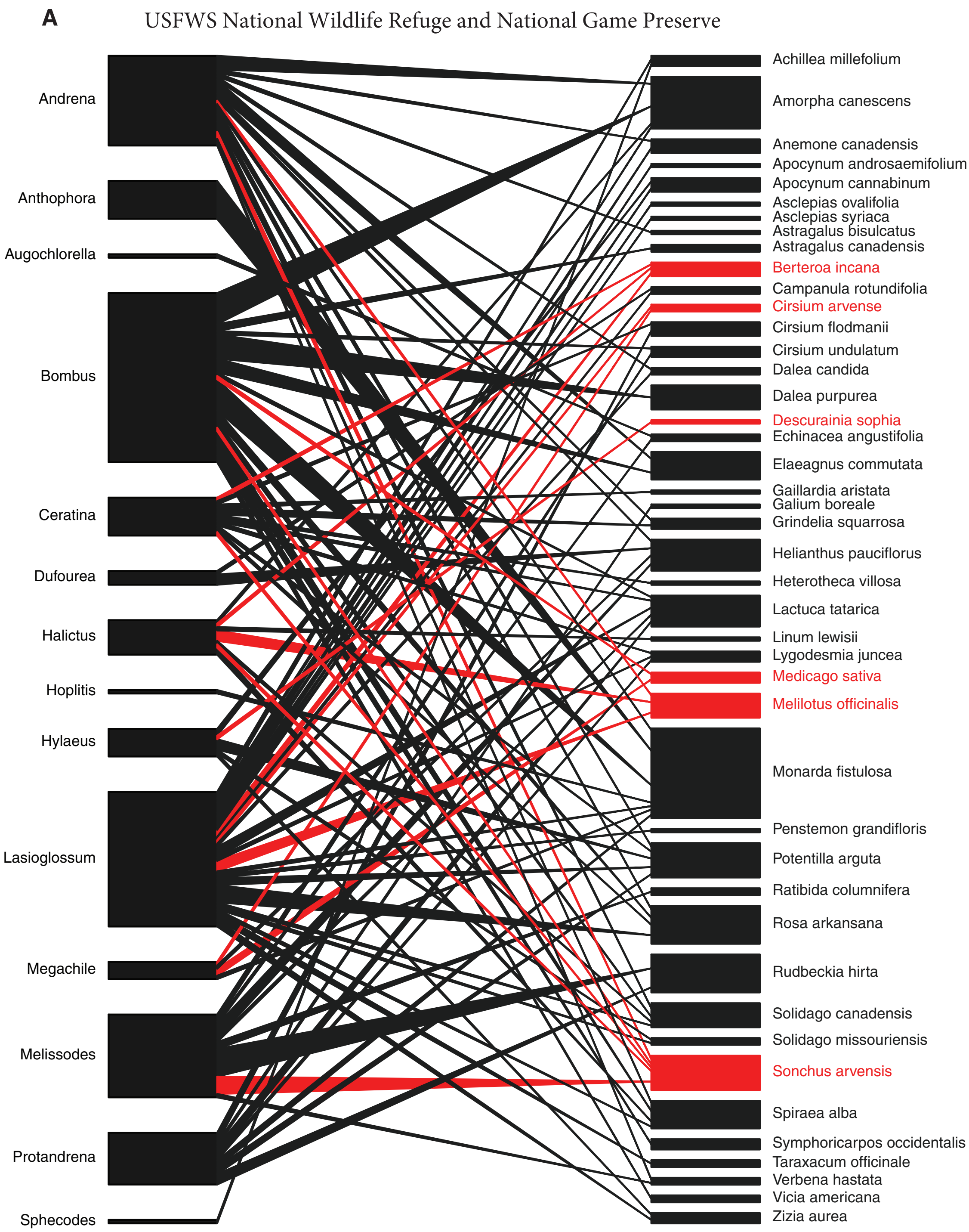

Fig. 3. Wild bee and plant interaction networks for (**A**) USFWS National Wildlife Refuges ($n = 210$), (**B**) USFWS-Waterfowl Production Areas ($n = 74$), and (**C**) USDA-Conservation Reserve Program ($n = 39$) lands in eastern North Dakota, 2012–2015. Red-nonnative plant, black-native plant. Block size next to a taxonomic name reflects the number of observations recorded in the Pollinator Library for that particular taxon. Data for USDA-Environmental Quality Incentives Program (EQIP) are not shown because no wild bee records exist for EQIP on the Pollinator Library as of October, 2016. (Online figure in color.)

interactions for multiple land-use types in ND (Figure 1). Wild bee observations consisted of 5 families, 15 genera, and 46 species detected on 63 unique species of plants (Table 2; Supp. Table 3 [online only]). The three most common wild bee genera detected were *Bombus* ($n = 67$), *Lasioglossum* ($n = 66$), and *Melissodes* ($n = 39$), representing ~55% of the total number of observations. Of the wild bee specimens identified to species, *Melissodes trinodis* Robertson ($n = 32$), *Halictus confusus* ($n = 25$), and *Bombus ternarius* Say ($n = 23$) were the most common. Accordingly, the majority of bee genera documented by the Pollinator Library were represented by <20 records (Fig. 2). The genus *Andrena* represented the highest wild bee species richness, with 15 species, though all species were represented by ≤3 records (Supp. Table 3 [online only]). Most of the wild bee observations occurred on USFWS National Wildlife Refuge

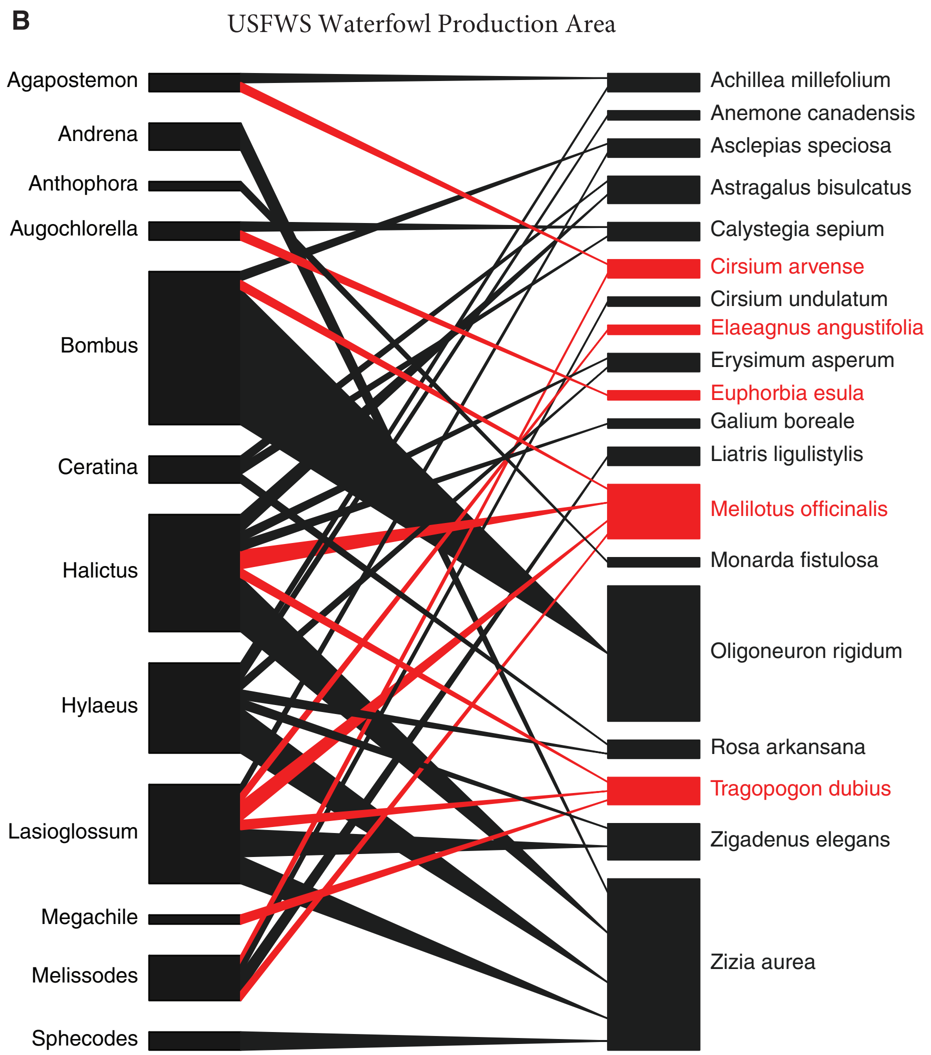

Fig. 3. continued.

and National Game Preserve lands ($n = 205$), followed by USFWS Waterfowl Production Areas ($n = 70$) and USDA CRP ($n = 39$). *Apis mellifera* observations occurred on CRP ($n = 437$), EQIP ($n = 57$), NWR ($n = 352$), and WPA ($n = 3$).

Wild Bee and Plant Interactions

Of the 63 unique species of plants detected, the most frequently visited plants were *Monarda fistulosa* ($n = 29$), *Sonchus arvensis* ($n = 26$), and *Zizia aurea* ($n = 22$), representing 24% of the total observations. Approximately 77% of all wild bee observations were made on plants native to ND, while the remaining observations (23%) were made on nonnative species. Surveys on NWR and WPA revealed wild bees visited a mix of native and nonnative flowers, whereas surveys conducted on CRP showed the predominant flowers visited were often nonnative plants such as *S. arvensis* and *Melilotus officinalis* (Fig. 3).

Apis mellifera and Plant Interactions

The 849 *A. mellifera* observations were represented by 18 plant species (Fig. 4; Supp. Table 3 [online only]). The top plants, representing 86% of all *A. mellifera* observations, were *Cirsium arvense* ($n = 282$), *M. officinalis* ($n = 236$), *Medicago sativa* ($n = 157$), and *S. arvensis* ($n = 51$). Among all *A. mellifera* interactions, 13% of the observations were made on plant species native to North Dakota, while 87% were made on nonnative species. *Apis mellifera* was more frequently observed on nonnative species on CRP (93%) and EQIP (90%) enrollments, relative to observations made on NWR (73%; Fig. 4).

Evaluating Hypothetical Seed Mixes

By conducting queried searches of plant–pollinator interactions available in the Pollinator Library and obtaining seed pricing from vendors, we were able to assess economic and biological tradeoffs associated with the hypothetical seeding mixes we developed. Based on data from the Pollinator Library, the 26-species mix included a greater number of wild bee species, genera, and individual bee observations than the 9-species or 3-species mixes (Fig. 5). The 26-species mix included all 15 bee genera available from our initial query of the Pollinator Library. The 26, 9, and 3-species mix represented 54%, 28%, and 8% of the total number of wild bee observations that we queried from Pollinator Library, respectively. The 3-species mix included the lowest number of wild bee species, genera, families and individual bee observations, but included the highest number of honey bee observations (Fig. 5E), constituting 46% of the total

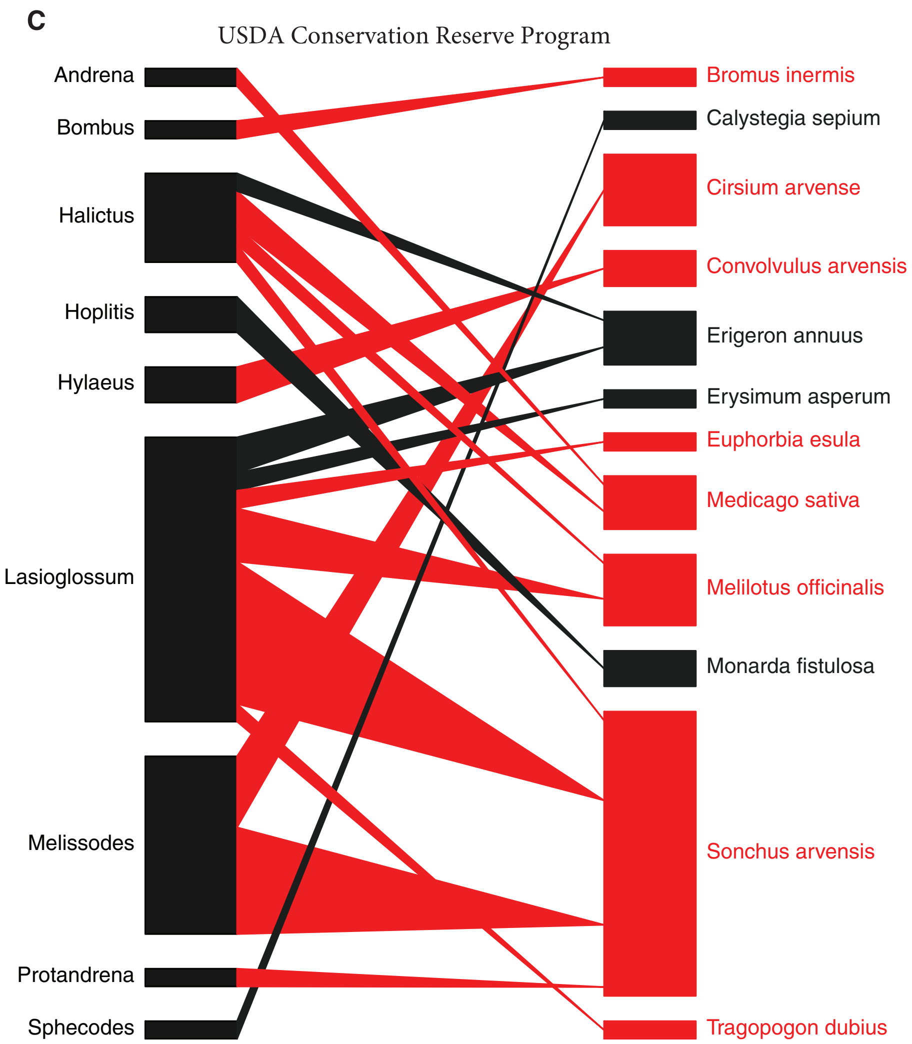

Fig. 3. continued.

number of honey bee observations queried from the Pollinator Library. The 26-species mix included the fewest number of honey bee observations among all mixes (12%). Our estimates of seeding cost for the 26, 9 and 3-species mixes were US$184, US$221, and US$39 per acre, respectively (Fig. 5F). There was considerable variation in wild bee visitation records among plants that were included in each seed mix (Fig. 6A). For example, the addition of *Monarda fistulosa* in the 26-species mix yielded 26 additional wild bee observations from the Pollinator Library, whereas the addition of *Penstemon grandifloras* yielded one additional wild bee observation (Fig. 6A). Conversely, the addition of forb species to seeding mixes did not appreciably increase the number of honey bee records queried from the Pollinator Library, except for selected species such as *Melilotus officinalis*, *Medicago sativa*, *Monarda fistulosa*, and *Dalea purpurea* (Fig. 6B). The 3-species mix included the highest number of honey bee interactions and was also the least expensive.

Discussion

Global population trends for wild bees and managed honey bees have generated considerable societal pressure to identify and mitigate potential anthropogenic stressors affecting pollinator populations (Goulson et al. 2015). Here, we summarize data collected in eastern North Dakota from 2012–2015 to document baseline occurrence of wild bees in this region and identify important forage plants for both wild bees and honey bees on public and private grasslands. Furthermore, we demonstrate how online, publically-available data can be used to improve ongoing conservation efforts for pollinators by evaluating the cost-effectiveness of seeding mixes. Our research is timely, considering several national programs designed to enhance pollinator habitat have recently been initiated in the NGP, a region currently undergoing significant land-use change (Wright and Wimberly 2013, Morefield et al. 2016), which threatens pollinator habitat (Otto et al. 2016). Our work builds upon research that has evaluated plant species and seeding mixes that may be attractive to pollinators (Tuell et al. 2008, Robson 2014, Harmon-Threatt and Hendrix 2015, Williams et al. 2015, M'Gonigle et al. 2016) by focusing on a region in the United States that is underrepresented in pollinator research, but is nonetheless an important part of the country for managed honey bees and wild bees (Koh et al. 2016, Smart et al. 2016a).

In the past decade, there have been a number of habitat conservation efforts for pollinators, and most recently the US Pollinator Health Task Force (2015) has set a goal of establishing or enhancing

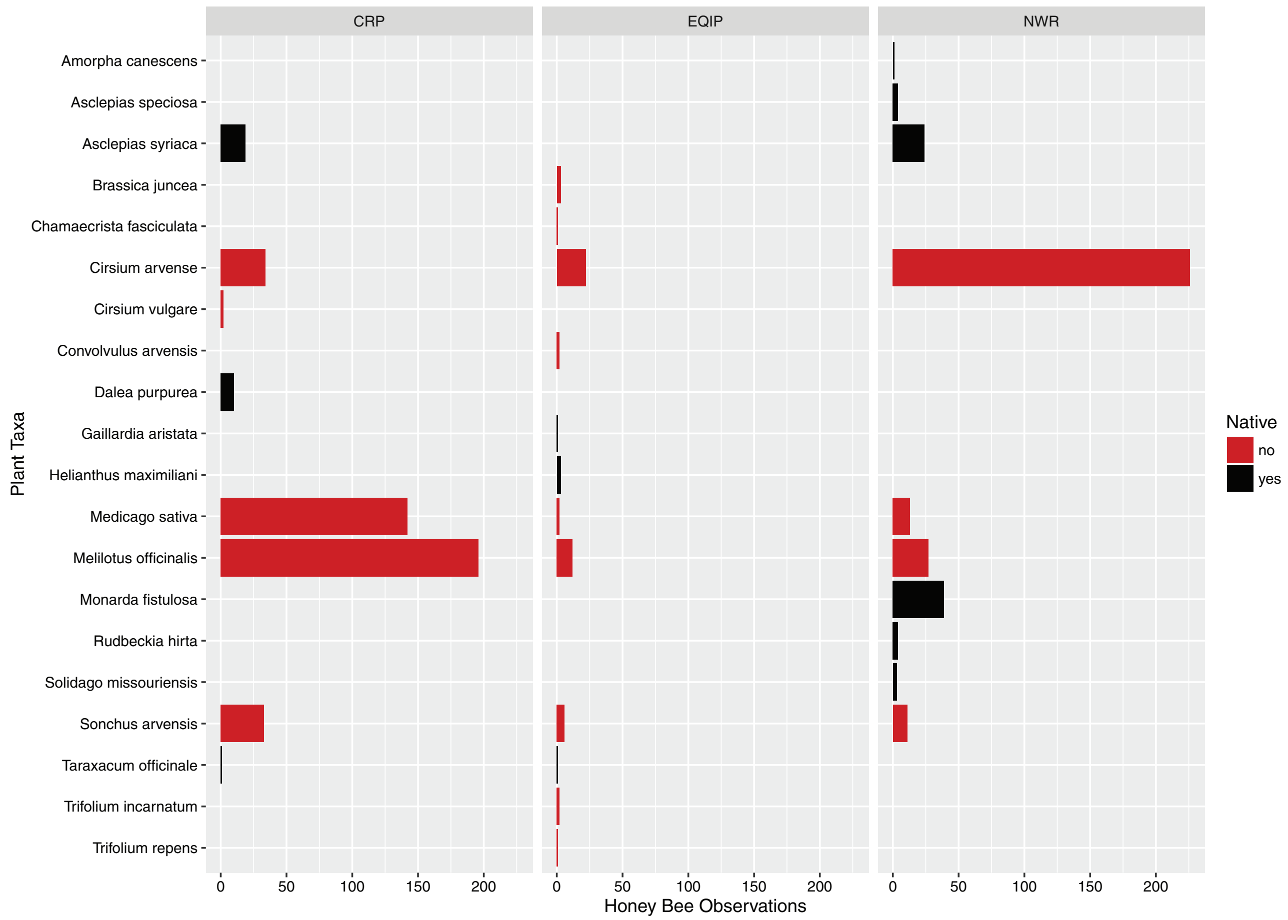

Fig. 4. *Apis mellifera* (i.e., honey bee) and plant interactions for USDA-Conservation Reserve Program ($n = 437$), USDA-Environmental Quality Incentives Program ($n = 57$), and USFWS National Wildlife Refuge ($n = 352$) lands in eastern North Dakota, 2012–2015. Red-nonnative plant, black-native plant. Data for USFWS-Waterfowl Production Areas ($n = 3$) are not shown owing to small sample size. (Online figure in color.)

7 million acres of pollinator habitat by 2020. Furthermore, the USDA has unveiled several conservation practices and initiatives for pollinators embedded within established programs such as CRP and EQIP. In 2014, both FSA and NRCS established separate initiatives that target the Upper Midwest and Northern Great Plains for pollinator enhancement. Although the management activities proposed within these initiatives vary, both initiatives focus on increased floral resources that benefit pollinators throughout multiple bloom cycles, while providing additional cost-sharing to the private landowners for seed mixes (https://www.fsa.usda.gov/Internet/FSA_Notice/crp_775.pdf, http://www.nrcs.usda.gov/wps/portal/nrcs/detail/national/plantsanimals/pollinate/?cid=stelprdb1263263) (accessed 12 February 2017). Although many studies have investigated floral resource use and preference of pollinating insects (Tuell et al. 2008, Morandin and Kremen 2013, Rollin et al. 2013, Robson 2014, Harmon-Threatt and Hendrix 2015), we are unaware of research that has used bee visitation data and seed cost to evaluate cost-effectiveness of conservation seeding mixes. Additional studies are needed to optimize the utility of new pollinator plantings, while also minimizing the financial burden to the landowner or government agencies assisting with field establishment. Although cost-effectiveness may not be an important evaluation criterion for all pollinator habitat enhancement efforts, we note cost-effectiveness is likely to be important for national programs that target private lands, such as the CRP and EQIP. Given that >60% of the United States, and 90% of ND, is privately owned, large-scale pollinator enhancement efforts are more likely to succeed if seed cost, which is incurred by landowners and taxpayers alike, is taken into consideration. Newly developed tools for evaluating pollinator plantings provide useful resources for land managers (Harmon-Threatt and Hendrix 2015, M'Gonigle et al. 2016) and can be further improved by incorporating seed cost as an evaluation criterion.

Although our seed mix assessment compares just three seeding mixes, and 1,163 plant–pollinator interaction records, it does provide useful guidance for natural resource managers and policy advisors, who are often tasked with making management decisions, with limited biological data for their target region. Our evaluation corroborates previous research highlighting the importance of forb diversity for supporting diverse wild pollinator communities (Isaacs et al. 2008, Morandin and Kremen 2013, Harmon-Threatt and Hendrix 2015). The species mix with the highest forb species richness (26-species mix) included the highest number of wild bee species, genera, families, and individual bee counts based on data from the Pollinator Library, whereas the mix with the lowest forb richness (3-species mix) represented the fewest wild bee species, genera, families and individual bee counts. Greater forb diversity provides continuous bloom throughout the growing season for polylectic bees, and also meets specific requirements of oligolectic bees (Larson et al. 2006, Larson et al. 2014, Fowler 2016).

Our seed mix evaluation also suggests that mixes may often need to be tailored to meet the unique needs of wild bees and managed honey bees in agricultural landscapes. Indeed, 46% of all honey bee

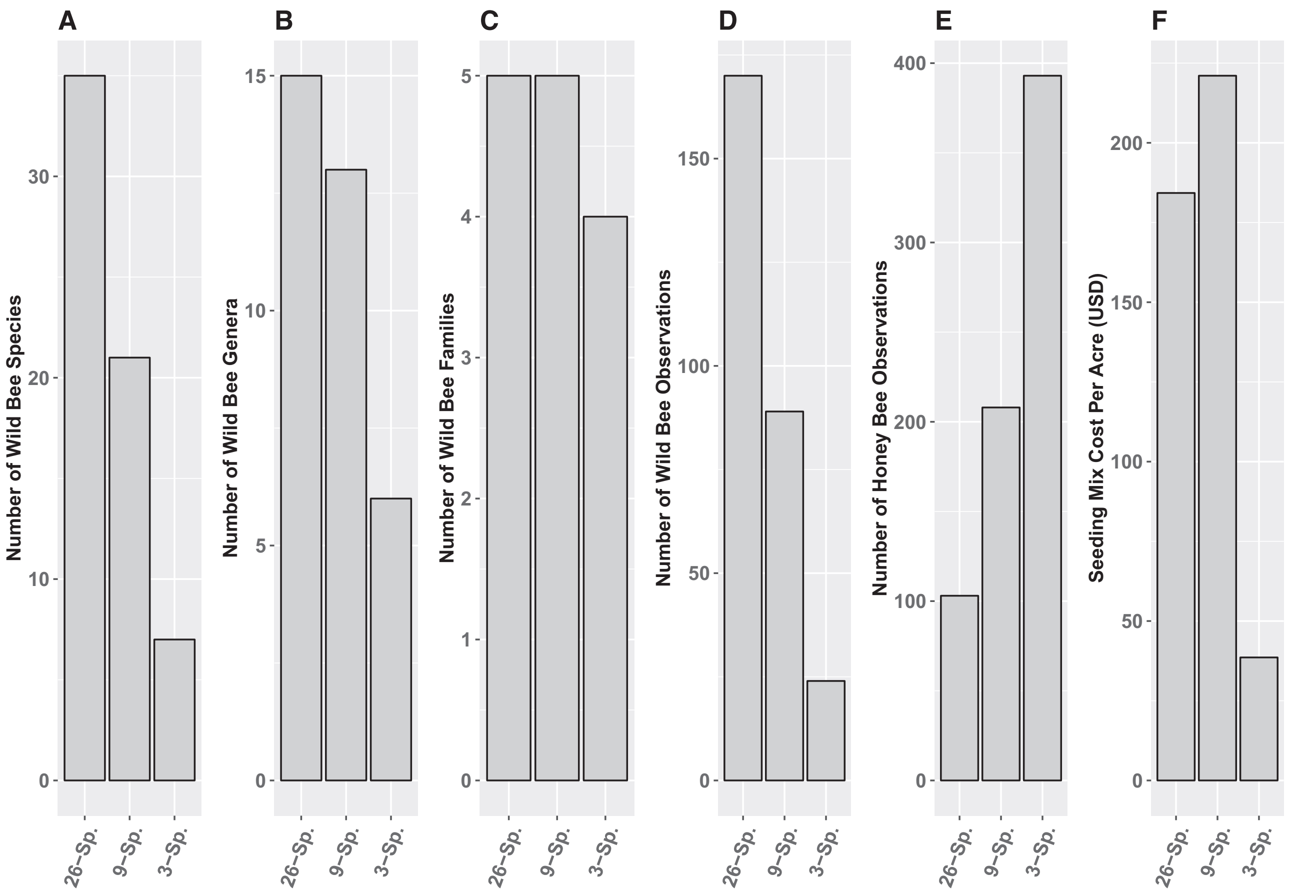

Fig. 5. Comparison of three hypothetical seeding mixes developed for pollinator plantings. We developed seeding mixes and matched forb species contained within each mix to plant–pollinator interaction data available for North Dakota in the Pollinator Library. For each mix, we report the number of wild bee species (**A**), wild bee genera (**B**), wild bee families (**C**), wild bee observations (**D**), and honey bee observations (**E**) queried from the Pollinator Library based on the forb species included in each seed mix. Estimated cost (USD) per acre is also reported (F). "3-Sp.," "9-Sp.," and "26-Sp." represent the 3-species mix, 9-species mix, and 26-species mix, respectively.

interactions observed could be represented by *M. officinalis*, and *M. sativa*. Based on our seeding cost assessment, seeding our 3-species mix, which included *M. officinalis* and *M. sativa*, in a new pollinator planting would cost ~US$39 (USD) per acre in the NGP. However, the low diversity seeding we evaluated is unlikely to meet the needs of a wild pollinator community; the 3-species mix represented just 8% of all wild pollinator observations. Current specifications for USDA's CRP Pollinator Habitat Practice (CP-42) require a minimum of nine forb species that bloom at different portions of the growing season. The 9-species mix we evaluated yielded 26 wild bee species, 91 wild bee observations, and 210 honey bee observations from the Pollinator Library. Interestingly, the 26-species mix generated a higher number of wild bee species and wild bee counts from the Pollinator Library, and was US$37 cheaper per acre than the 9-species mix. This finding is important considering that higher diversity pollinator plantings are often assumed to cost landowners considerably more than lower diversity plantings. Landowner perception of higher diversity equating to higher monetary cost may influence landowner decisions whether to enroll in pollinator habitat programs. Our evaluation demonstrates that the cost of higher diversity seeding mixes can be comparable with lower diversity seeding mixes, as long as seeding rates are kept at a reasonable level. Here, we show that a 26-species mix can be achieved for an estimated US$184 per acre with a standard seeding rate of 40 seeds per ft^2. This savings was achieved by using a seed mix calculator that designs seeding specifications according to seeds per ft^2 as opposed to PLS pounds per acre, which does not take into account the variable seed sizes of forb species. In this research, we made several assumptions about seeding density for individual forb species based on prior knowledge and field experience for successfully establishing a mixed stand of forbs and grasses. However, we were unable to evaluate how altering seeding density and seeding patch size would affect forb biomass, forb diversity, and seed cost if these hypothetical mixes were actually purchased and seeded. Seeding density and patch size can directly affect stand productivity and diversity when establishing grasslands (Seahra et al. 2015, Dickson and Busby 2009), and in turn affect how bee species interact with the established forb community in some systems (Dauber et al. 2010, Blaauw and Isaacs 2014). Additional research is needed to understand how seeding density and spatial patterns affects forb productivity and mutualistic interactions with pollinator communities on newly established conservation plantings.

Recent literature has raised the concern of floral resource competition between wild bees and honey bees (Cane and Tepedino 2016, Thomson 2016). Although our study was not designed to investigate interspecific competition, it does highlight how wild bees and honey bees may co-occur in the same landscape, and yet utilize a different spectrum of the floral resource community. Differential floral resource use between wild bees and honey bees has been observed in other agroecosystems (Rollin et al. 2013) and interspecific

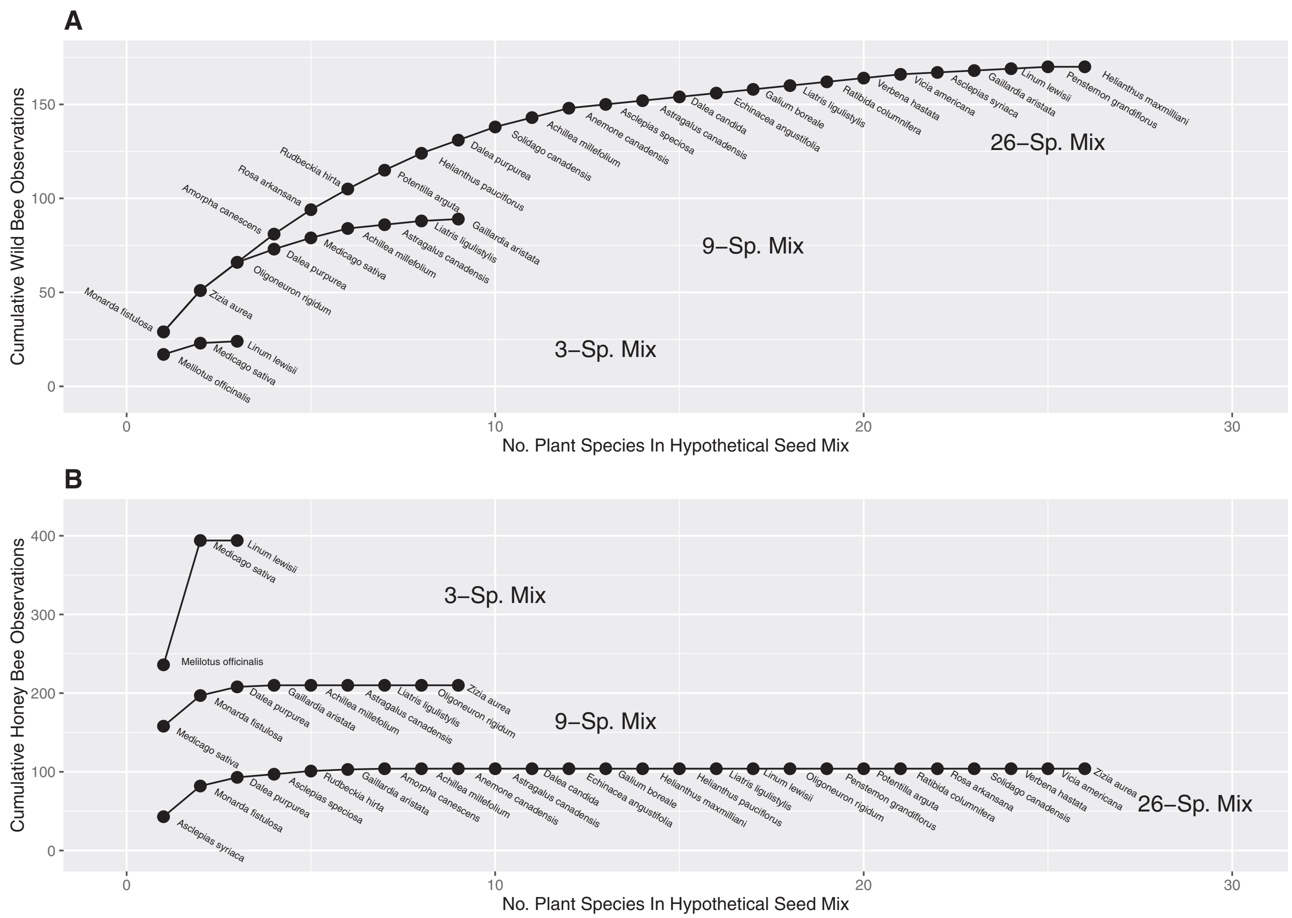

Fig. 6. Cumulative wild bee (**A**) and honey bee (**B**) observations queried from the Pollinator Library for each plant species included in hypothetical seed mixes. The horizontal axis represents the number of plant species included in each hypothetical seed mix. The vertical axis represents counts of bee observations based on queried searches of the Pollinator Library and the plant species included in each hypothetical mix. "3-Sp. mix," "9-Sp. mix," and "26-Sp. mix" represent the 3-species mix, 9-species mix, and 26-species mix, respectively.

competition can be potentially mediated by habitat quality (Herbertsson et al. 2016). Given the recent increase in the number of registered honey bee colonies in ND (United States Department of Agriculture 2014), and coupled with loss of pollinator habitat and wild pollinator declines in the NGP (Koh et al. 2016), there is a need for additional research on potential competition between honey bees and wild pollinator communities in this region.

Our study further highlights the importance of nonnative plants in providing forage for honey bees, and to a lesser extent, wild bees, existing in the agricultural landscape of North Dakota (Smart et al. 2016b, Smart et al. 2017). The four most frequently visited plants by honey bees were nonnative species and 23% of our wild bee observations were made on nonnative plants. However, our study does not quantify bee preference of forbs, which could influence our overall conclusions if bees are simply utilizing plants consistent with their abundance on the landscape (Williams et al. 2011). We were unable to quantify preference in this study because the Pollinator Library provides specific information on individual plant–pollinator interactions, but does not provide information on abundance of various plant species surrounding the observed plant–pollinator interaction (i.e., forb availability). Furthermore, the individual field studies summarized by our research either 1) did not collect forb abundance data, or 2) had significant methodological variation in quantifying forb abundance. Future studies could benefit from quantifying bee preference, particularly when it comes to honey bee and wild bee forage on nonnative, or potentially invasive plants (i.e., plants that are nonnative and cause economic or environmental harm). Although we did not quantify preference, our results add to a growing body of evidence on the importance of nonnative species for honey bees and wild bees in landscapes where native plants have been removed owing to land-use conversion (Bretagnolle and Gaba 2015, Rollin et al. 2016). While managing for nonnative plant species may not be a shared goal among all stakeholders, we note that nonnative plants have been used to restore ecosystem function and provide habitat for native wildlife in degraded ecosystems (Schlaepfer et al. 2011). Nonnative plants have been used in grassland conservation programs in the NGP in part owing to their adaptability, ecological tolerance, and low financial cost.

Although the importance of federal lands and programs for promoting pollinator habitat has been discussed in the literature and popular press, relatively few studies have attempted to quantify the role of federally owned lands, or private lands enrolled in federal programs, in providing habitat and forage for pollinators in intensively managed agroecosystems (Otto et al. 2016). Our study highlights the important, and potentially different, roles played by public and private lands in agroecosystems. Wild bee observations summarized in this study demonstrate the importance of federally owned lands for providing forage plants for wild bee species in intensively managed landscapes. Indeed, intensive sampling of wild bee communities in North Dakota revealed higher richness and diversity of wild bees on NWR than CRP (Bryant 2015). Although our study provides relatively few wild bee observations on CRP, it does highlight the importance of private lands enrolled in USDA conservation programs for supporting honey bee forage and some wild pollinators. It is important to note that our current study does not take into account CRP practice type, field size, or contract age, which are important factors influencing stand vegetation structure and the pollinator communities found therein. Given the importance of private land conservation programs in the NGP, understanding how factors such as field size, contract age, management techniques, and conservation practice type play a role in supporting wild pollinator communities would be tremendously valuable. Nonetheless, our current findings are important considering the known value of USDA grassland programs, and other uncultivated grasslands, for improving honey bee colony habitat, health, and survival in the NGP (Gallant et al. 2014, Otto et al. 2016, Smart et al. 2016b). Honey bee colonies that spend the summer in the NGP are often transported throughout the United States for crop pollination during the winter. By providing forage for migratory honey bee colonies in the summer, conservation grasslands in the NGP likely have a positive effect on agricultural crop pollination elsewhere in the United States; however, this apparent association still needs to be quantified. Given the rapid rate of land-use change in the NGP (Wright and Wimberly 2013, Morefield et al. 2016), there is a growing need for ecologists and economists to quantify the societal costs and ecosystem services associated with federally-funded conservation programs that target private lands (Euliss et al. 2010, Johnson et al. 2016).

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