Past role and future outlook of the Conservation Reserve Program for supporting honey bees in the Great Plains

Clint R. V. Otto[a,1], Haochi Zheng[b], Alisa L. Gallant[c], Rich Iovanna[d], Benjamin L. Carlson[a], Matthew D. Smart[a], and Skip Hyberg[d]

[a]Northern Prairie Wildlife Research Center, US Geological Survey, Jamestown, ND 58401-7317; [b]Department of Earth System Science and Policy, University of North Dakota, Grand Forks, ND 58202-9011; [c]Earth Resources Observation and Science Center, US Geological Survey, Sioux Falls, SD 57198; and [d]Farm Service Agency, US Department of Agriculture, Washington, DC 20250-0519

Edited by May R. Berenbaum, University of Illinois at Urbana–Champaign, Urbana, IL, and approved May 29, 2018 (received for review January 3, 2018)

Human dependence on insect pollinators continues to grow even as pollinators face global declines. The Northern Great Plains (NGP), a region often referred to as America's last honey bee (*Apis mellifera*) refuge, has undergone rapid land-cover change due to cropland expansion and weakened land conservation programs. We conducted a trend analysis and estimated conversion rates of Conservation Reserve Program (CRP) enrollments around bee apiaries from 2006 to 2016 and developed models to identify areas of habitat loss. Our analysis revealed that NGP apiaries lost over 53% of lands enrolled in the CRP, and the rate of loss was highest in areas of high apiary density. We estimated over 163,000 ha of CRP lands in 2006 within 1.6 km of apiaries was converted to row crops by 2012. We also evaluated how alternative scenarios of future CRP acreage caps may affect habitat suitability for supporting honey bee colonies. Our scenario revealed that a further reduction in CRP lands to 7.7 million ha nationally would reduce the number of apiaries in the NGP that meet defined forage criteria by 28% on average. Alternatively, increasing the national cap to 15 million ha would increase the number of NGP apiaries that meet defined forage criteria by 155%. Our scenarios also show that strategic placement of CRP lands near existing apiaries increased the number of apiaries that meet forage criteria by 182%. Our research will be useful for informing the potential consequences of future US farm bill policy and land management in the epicenter of the US beekeeping industry.

agriculture policy | farm bill | land-use change | Conservation Reserve Program | pollinator

Insect pollinators play a critical role in supporting ecosystem function, global agriculture, and human health (1, 2). Concurrent loss of honey bees (*Apis mellifera*) and native bees has raised significant concern over food security, human health, and agricultural productivity, particularly in the United States, where insect pollination services are valued at over $15 billion US dollars (USD) annually (3, 4). US beekeepers have experienced >30% annual colony loss in recent years (5), and native bee populations and other iconic insects such as monarch butterflies (*Danaus plexippus*) are declining throughout the United States (6, 7). The rusty patched bumble bee (*Bombus affinis*), once found throughout the Midwest, was officially listed as an endangered species in 2017. Pollinators face myriad threats, including habitat loss, diseases, pathogens, pesticide exposure, and limited floral resources (8, 9). As with much of biodiversity, the principal threat facing many pollinators on a global scale is habitat loss. The US Pollinator Health Task Force (PHTF) was assembled to address pollinator declines in response to habitat loss and other threats. The PHTF established three key goals, two of which included reducing colony losses of overwintering honey bees to no more than 15% and restoring or enhancing 2.8 million ha [7 million acres (ac)] of land for pollinators by 2020. Achieving these goals will require a joint effort between government entities and individual citizens, scientific evaluation of critical areas for conservation delivery, and effective monitoring to ensure that established habitat has the desired outcome on pollinator health.

Since the first farm legislation in 1933, US farm bills have been one of the most influential federal policies for agriculture and food production. Provisions within farm bills have profound influence on global trade, nutrition programs, commodity crop programs, rural communities, and land conservation. Since the Food Security Act in 1985, farm bills have included provisions for placing marginal cropland into long-term conservation covers under the Conservation Reserve Program (CRP). The CRP is a voluntary, private-lands program where landowners receive an annual rental payment from the US Federal Government for the duration of the contract (typically 10–15 y) and additional cost-sharing for establishing and maintaining these conservation covers, often in the form of grassland in the Great Plains. At its peak in 2006, the CRP had over 14.6 million ha (36 million ac) of land enrolled nationally; however, the maximum permitted enrollment was reduced under the 2008 and 2014 Farm Bills, and is currently set at 9.7 million ha (24 million ac). Originally designed to reduce soil erosion and improve soil health on marginal lands, subsequent farm bills have expanded the goals of the CRP, including improving water quality and providing wildlife habitat. Other ecosystem services provided by CRP lands include reducing greenhouse gas emissions; groundwater recharge; furnishing grazing lands for cattle during drought; and, most recently, supporting pollinator forage (10–13).

Significance

Global pollinator declines have raised significant concern over food security, human health, and agricultural productivity. Our work highlights how the Conservation Reserve Program (CRP) has a direct influence on landscape suitability for supporting honey bee apiaries in a region harboring >1 million colonies. Our analysis revealed recent conversion of CRP grassland to annual crops in core areas of the commercial beekeeping industry, thereby reducing forage lands for honey bees at a time when the number of colonies in this region has never been greater. Our land-use scenario models provide policy makers with direct information on how future CRP acreage caps established by the US Congress will affect the environmental carrying capacity for supporting honey bees and the US beekeeping industry.

Author contributions: C.R.V.O., H.Z., A.L.G., R.I., M.D.S., and S.H. designed research; C.R.V.O., H.Z., A.L.G., and B.L.C. performed research; C.R.V.O., H.Z., A.L.G., and B.L.C. analyzed data; and C.R.V.O., H.Z., A.L.G., and M.D.S. wrote the paper.

The authors declare no conflict of interest.

This article is a PNAS Direct Submission.

This open access article is distributed under Creative Commons Attribution-NonCommercial-NoDerivatives License 4.0 (CC BY-NC-ND).

[1]To whom correspondence should be addressed. Email: cotto@usgs.gov.

This article contains supporting information online at www.pnas.org/lookup/suppl/doi:10.1073/pnas.1800057115/-/DCSupplemental.

Some of the most drastic losses of CRP land have occurred in the Northern Great Plains (NGP) (14), a region supporting ~40% of US honey bee colony stock. Often referred to as the last frontier of the commercial beekeeping industry, the Prairie Pothole Region (PPR) within the NGP is perhaps the most important part of the country for providing pasturing grounds for honey bees during the summer (9). Beekeepers transport their colonies to this part of the United States because growing season weather and land cover provide optimal conditions for raising healthy bee colonies. Land-use changes in other parts of the country, and ideal conditions for blooming flowers, have resulted in an influx of commercial beekeepers and their honey bee colonies to the NGP during the summer. For example, in North Dakota and South Dakota, two states that constitute the majority area of the PPR, the number of registered honey bee colonies rose from 575,000 to 780,000 from 2006 to 2015 (15–18). Colonies that spend the summer in the NGP subsequently are transported throughout the country to pollinate a variety of agricultural crops during the late winter and spring (19). Previous work has demonstrated the importance of grassland, and specifically CRP lands, in improving habitat suitability for honey bee colonies in the NGP (12, 20). Furthermore, the area of uncultivated grasslands in the NGP is directly related to colony survival in California during almond pollination (21), an agricultural crop worth over $5 billion USD annually (22). Grasslands and CRP lands are preferred by beekeepers when selecting apiary sites because these land-cover types provide honey bees access to flowering plants throughout the growing season (12, 20, 23). Since the early 2000s, significant land-use changes have taken place within the NGP and PPR; grassland and pasture have been converted to annual crops due, in part, to high commodity prices and incentives for growing corn and soybeans (24).

Given the current downward trend in national CRP acreage and growth in registered honey bee colonies in the NGP, there is considerable uncertainty how this might affect the health of honey bee colonies and the commercial beekeeping industry, as well as the pollination services provided to the entire United States. Furthermore, it is unclear what CRP enrollments are being converted to once their contracts expire, where these conversion are occurring, and whether the NGP beekeeping industry could be affected. With commodity crop prices decreasing since 2015, and smaller profit margins for producers, some landowners will seek alternatives to crop production. The CRP and other conservation programs are likely to be reexamined as the 2018 Farm Bill is written. Debates over government-supported conservation programs often focus on budgetary cost to the government, without considering the benefits provided to farmers and the ecosystem services provided to society. Here, we investigate temporal trends and conversion rates of CRP land around 18,363 registered apiary locations in North Dakota and South Dakota from 2006 to 2016 and develop scenario models to evaluate how future changes in CRP acreage may alter landscape suitability for supporting managed honey bee colonies. We further consider how conversion rates may have differed within the PPR versus elsewhere in North Dakota and South Dakota, given differences in land characteristics.

Our research goals were to (*i*) quantify CRP area trends around registered apiaries in North Dakota and South Dakota, (*ii*) determine whether expired or terminated CRP enrollments near registered apiaries remained in grassland or were put back into agricultural production, (*iii*) investigate whether changes in CRP area have been occurring in areas supporting higher densities of registered apiaries, and (*iv*) evaluate the changes in suitability of the NGP landscape for supporting commercial apiaries under a suite of CRP acreage allocation scenarios. Our research addresses multiple information gaps with respect to pollinator health, agricultural policy, and ecosystem services provided by federally funded conservation programs.

Results

CRP Trends Around Apiaries. Our linear model revealed a consistent downward trend in the area of the CRP surrounding 18,363 registered apiary locations (*SI Appendix*, Fig. S1) from 2006 to 2016 both within and outside the PPR of North Dakota and South Dakota (*SI Appendix*, Fig. S2*A*). In general, the greatest losses of CRP area occurred throughout much of the eastern and central potions of North Dakota (i.e., the PPR in North Dakota), northern portions of South Dakota, and arable regions outside the PPR (Fig. 1). Counties with the highest density of apiaries tended to exhibit the greatest loss of CRP area (Fig. 1). In 2006, the average area of the CRP around registered apiary locations within the PPR was $\bar{x}_{CRP\_2006} = 89.4 \pm 109.8$ ha (1 SD), representing $10.9 \pm 13.5\%$ of the total land area within a 1.6-km radius of apiaries. In 2016, the average area of the CRP around PPR apiaries was reduced to $\bar{x}_{CRP\_2016} = 41.7 \pm 64.4$ ha, or $5.1 \pm 7.9\%$ of the total land area within a 1.6-km radius of apiaries. Thus, there was a 53% loss of CRP area surrounding registered apiaries from 2006 to 2016 in the PPR of North Dakota and South Dakota. In 2006, the area of the CRP around apiaries outside the PPR in North Dakota and South Dakota averaged $\bar{x}_{CRP\_2006} = 42.8 \pm 83.1$ ha, or $5.3 \pm 10.2\%$ of the total land area within a 1.6-km radius of apiaries. In 2016, the average area of the CRP around non-PPR apiaries was reduced to $\bar{x}_{CRP\_2016} = 22.7 \pm 55.9$ ha, or $2.8 \pm 6.9\%$ of the total land area, representing a 47% loss relative to 2006. Across North Dakota and South Dakota, lands enrolled in the CRP in 2006 around apiaries represented 18.9% of the total area of grassland (399.7 ± 198.1 ha), as classified by the 2006 Cropland Data Layer (CDL). The three most common CRP conservation practices around apiaries in 2016 were Established Grass Cover (CP-10), Duck Nesting Habitat (CP-37), and Permanent Wildlife Habitat (CP-04D) (*SI Appendix*, Fig. S3).

CRP Conversion. Of the 879,242 ha of the CRP within 1.6 km of apiaries in North Dakota and South Dakota in 2006, 19%, totaling 163,304 ha, was converted to annual crops by 2012 and remained in crop production for at least 5 y (Fig. 2). Over 67% (110,687 ha)

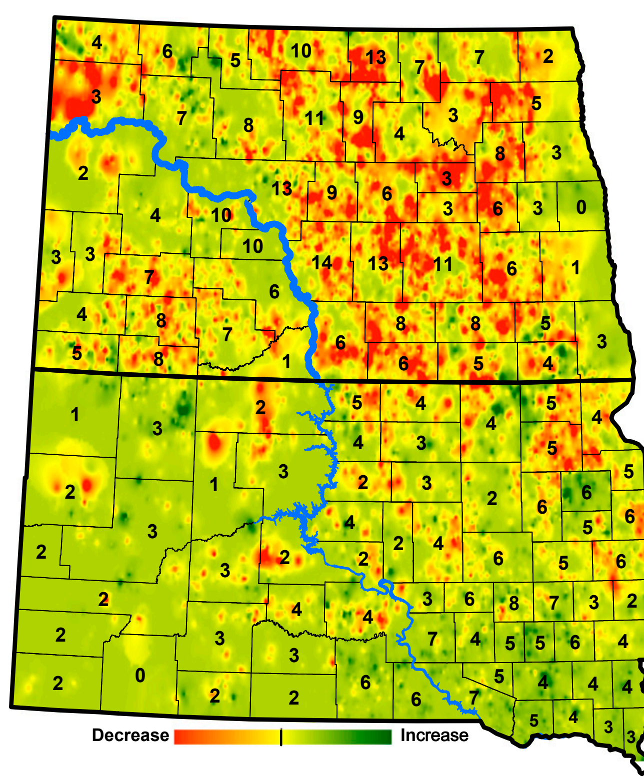

Fig. 1. Heat map showing the relative change in CRP area within 1.6 km of 18,363 registered apiaries in North Dakota and South Dakota from 2006 to 2016. The PPR is east and north of the Missouri River (indicated in blue). Values within county boundaries represent the number of registered apiaries per 40 km^2. Locations where CRP area decreased, remained static, or increased are represented as red, yellow, and green, respectively.

of converted CRP land was first planted as corn or soybeans; all other crop types constituted 33% (52,618 ha) of converted CRP land (Fig. 2). From 2007 to 2012, 8% (13,514 ha) of converted CRP land was planted as sunflower, canola, or alfalfa (*SI Appendix*, Fig. S4). We note that our CRP conversion estimates may be biased low, relative to the actual area of converted CRP land, because our 5-y criterion was a conservative approach applied to overcome potential mapping errors in the annual land-cover data. Our analysis suggests conversion of CRP land to cropland remained high even after 2012; we detected that 191,668 ha of CRP land were converted from 2013 to 2016. However, estimates for these years may be biased high, as data were not available for five subsequent years of cropping history to substantiate the reliability of conversions mapped after 2012.

CRP Changes and Apiary Density. Townships in the PPR had nearly double the number of registered apiaries [$\bar{x}_{\text{Apiaries}} = 6.3 \pm 5.4$ (1 SD)] and more than double the area of CRP land in 2016 (336.8 ha ± 370.6) than townships elsewhere in North Dakota and South Dakota ($\bar{x}_{\text{Apiaries}} = 3.4 \pm 4.1$, $\bar{x}_{CRP} = 136.0$ ha ± 293.8). Our generalized linear model revealed a significant negative correlation between the change in CRP area (ha) from 2006 to 2016 and the number of registered apiaries per township in 2015 (*SI Appendix*, Fig. S5). Specifically, townships with a higher number of registered apiaries exhibited greater loss of CRP area from 2006 to 2016 and townships with fewer registered apiaries tended to lose less CRP area [$\beta_{\Delta CRP} = -0.00054 \pm 0.000013$ (±1 SE), z value = −39.8, $P < 0.001$].

Apiary Suitability and CRP Scenarios. We used simulation models to understand how multiple CRP scenarios could affect landscape suitability for supporting apiaries. Under the scenario of a national CRP cap of 7.7 million ha (19 million ac), our model estimated an average 28% decrease (range: 19–34%) in the number of apiaries in North Dakota and South Dakota that could meet the forage criteria from three published studies, relative to the 2016 CRP baseline (Fig. 3 and *SI Appendix*, Fig. S6 and Table S1). On average, there was a 20.2% reduction in CRP area around apiaries under this scenario, relative to 2016. We also considered a 7.7-million-ha scenario where CRP enrollments located within 3.2 km of apiaries were preferentially maintained, while CRP enrollments beyond this distance were allowed to expire. This scenario represents a national reduction in CRP area, while recognizing the value of CRP land as pollinator habitat. Under the strategic reduction scenario, there was an average 18% decrease

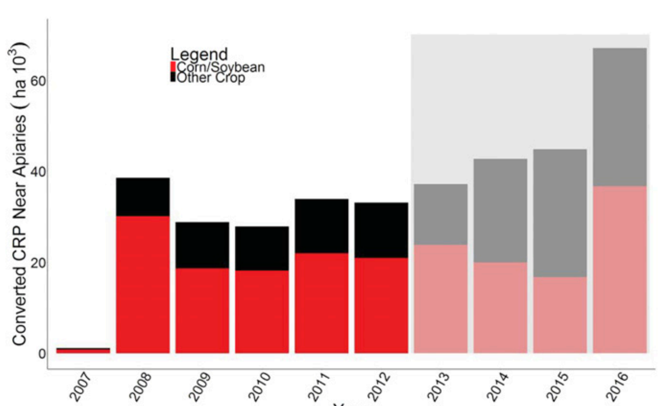

Fig. 2. Hectares of CRP land converted to annual crops (red, corn/soybeans; black, all other crops) within 1.6 km of registered apiaries in North Dakota and South Dakota from 2007 to 2012 that remained mapped as crops for ≥5 y. Estimates of converted CRP land for 2013–2016 are also shown, but there was progressively less than 5 y of postconversion information to corroborate these estimates; hence, the rate of change shown for 2013–2016 represents successively less control for mapping error.

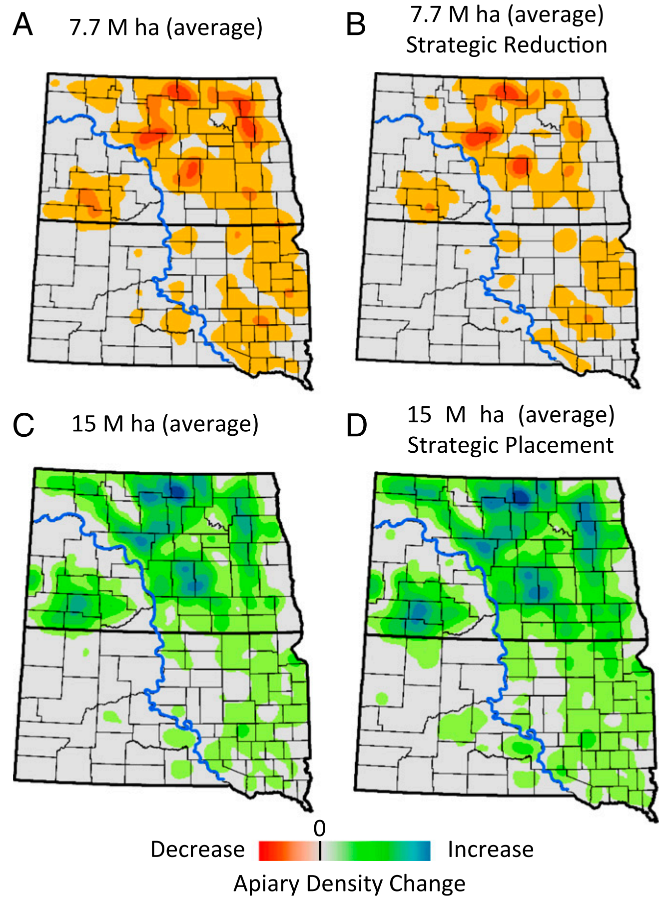

Fig. 3. Density maps of registered apiaries that met forage criteria for honey bees (*Methods*) under four CRP scenarios: 7.7-million-ha national CRP cap (*A*); 7.7-million-ha national CRP cap, where CRP land was strategically removed to minimize forage loss around apiaries (*B*); 15.0-million-ha national cap (*C*); and 15.0-million-ha national cap with strategic placement of CRP land within 3.2 km of existing apiaries (*D*). The color gradient depicts changes in the numbers of apiaries meeting CRP-related forage criteria under each scenario, relative to the 2016 CRP baseline. Maps represent average outcomes across the multiple forage criteria we used. Specific outcomes for each forage criterion and the 2016 CRP baseline can be found in *SI Appendix*, Fig. S5.

(range: 13–20%, across the three criteria) in the number of apiaries in North Dakota and South Dakota that met the CRP forage criteria, relative to the 2016 baseline (Fig. 3 and *SI Appendix*, Fig. S5 and Table S1). On average, there was a 19% reduction in CRP area around apiaries under this scenario, relative to 2016.

Under the CRP scenario of 15 million ha (37 million ac), there was an average 155% increase (range: 68–210%, across the three criteria) in the number of apiaries in North Dakota and South Dakota that met the CRP-related forage criteria, relative to the 2016 baseline (Fig. 3 and *SI Appendix*, Fig. S5 and Table S1). Under this scenario, the area of CRP land around apiaries increased, on average, by 93%, relative to the 2016 baseline. We also considered a 15.0-million-ha scenario where new CRP enrollments were prioritized within 3.2 km of registered apiaries (i.e., honey bee foraging distance). This scenario represented strategic establishment of CRP land in close proximity to honey bee colonies. Under this strategic scenario, there was an average 182% increase (range: 75–252%, across the three criteria) in the number of apiaries that met the CRP forage criteria, relative to the 2016 baseline (Fig. 3 and *SI Appendix*, Fig. S5 and Table S1). Furthermore, the area of CRP land within 3.2 km of apiaries increased by 200% under this scenario, relative to the baseline. For all scenarios, the benefits of adding, or disadvantages of losing, CRP land to support apiaries was most evident in areas east of the Missouri River that are generally classified as having marginal soils (Fig. 3 and *SI Appendix*, Fig. S5).

Discussion

Our work provides insight into how recent farm bill and land-cover changes have reduced CRP forage land for honey bees in close proximity to apiary locations in the NGP, a region supporting >1 million honey bee colonies annually. Private lands enrolled in the CRP are actively targeted by beekeepers when selecting apiary sites because of the floral resources these lands provide (12, 20, 23). We show a systematic trend in CRP loss over the past 10 y, with the most drastic declines occurring in areas that support the highest numbers of apiaries. Detecting a greater loss of CRP land in areas of higher apiary density is not surprising, given that beekeepers often locate their apiaries in heterogeneous landscapes with marginal cropland, where land-use decisions are heavily dictated by commodity crop prices (25, 26). Our conversion analysis encompassed a time span of high-commodity crop prices and reduced CRP acres and farm bill conservation program funding, thereby suggesting a role of federal policy in influencing land-use changes and landowner decisions, and the implications on bee forage lands. For example, our analysis revealed that in 2007, <1,400 ha of CRP land around apiaries was converted to cropland, whereas in 2008, ≈39,000 ha of CRP land around apiaries was converted to cropland, and much of the converted CRP land was first planted as corn or soybeans.

In 2006, corn and soybean prices were $3.04 and $6.43 per bushel, respectively (27). By 2012, corn and soybean prices climbed to $6.89 and $14.40, and have decreased since then (27). Our study showed that from 2007 to 2012, >60% of all of the converted CRP land around apiaries was first planted as corn or soybeans, suggesting that high commodity prices and/or bioenergy incentives for corn-based ethanol and soybean-based biodiesel influenced landowner decisions to convert CRP to cropland (24, 26). The conversion of CRP to corn and soybeans likely reduces landscape suitability for honey bees because it eliminates important forage lands for pollinators and replaces them with crops of limited forage value. In addition, corn and soybeans are often intensively treated with a variety of agrochemicals that can negatively affect colony health through multiple pathways (28–30). For example, neonicotinoids, a class of systemic insecticides that are applied to >80% of corn and >35% of soybean seeds (31) have negative effects on bee health and services (32, 33). Beekeepers avoid placing their apiaries near large expanses of corn and soybeans because of the limited forage value and potential pesticide exposure (20, 34, 35). We also detected that only 8% of all converted CRP land was first planted as sunflower, canola, or alfalfa, further demonstrating that the vast majority of CRP land is not being replaced with crops that provide pollinator forage value. Thus, our conversion analysis suggests that the NGP has been replacing pollinator-friendly forage lands with land covers posing significant threats to pollinator health, at a time when societal concern for pollinators has never been greater. In addition to loss of forage lands for pollinators, conversion of CRP land to annual crops can affect the delivery of other known ecosystem services provided by the CRP, such as improving soil health, providing wildlife habitat, and sequestering carbon (11, 36, 37).

The observed trends in declining pollinator habitat are troubling, considering the influx of ≈190,000 new honey bee colonies in North Dakota and South Dakota from 2006 to 2016 (15–18). These trends suggest the US beekeeping industry is increasingly reliant on the NGP in providing refuge for honey bee colonies at a time when the carrying capacity of this landscape for supporting colonies is decreasing. Ecological theory suggests that substantial population increases without concurrent increases in carrying capacity can lead to greater levels of competition among honey bee colonies and among beekeepers for safe and productive pasturing grounds. Increased competition and lack of floral resources have been proposed as primary drivers of pollinator declines (8). Further loss of honey bee colonies could destabilize crop pollination in multiple parts of the United States and further strain the financial solvency of the beekeeping industry, whose revenue is based on honey production and pollination service rental payments. Although few data are available to infer increasing competition among beekeepers, long-term records show that honey production per colony has decreased since 2000, even as the total amount of honey produced nationally has remained relatively constant (15–18). Furthermore, the apiary registration database we used for North Dakota shows beekeepers exhibit substantial overlap in their operating domains and often register apiaries within 2 km of one another. Although the density of colonies per apiary varies across our region, published estimates for North Dakota suggest 48 colonies per apiary (21). A higher density of apiaries, or a higher number of honey bee colonies per apiary, in remaining forage areas has the potential to reduce per-colony honey yields and increase disease transmission (38). Potential competition with native bees is also of concern in landscapes that are depauperate of floral resources (39), as habitat availability plays a direct role in mediating outcomes of competitive interactions between honey bees and native bees (40).

Our scenario models demonstrate considerable risk and opportunity to be considered for current and future conservation programs with respect to pollinator habitat. Whereas our trend analysis revealed that CRP acreage has declined by >50% around apiaries in North Dakota and South Dakota since 2006, our scenario models estimate that increasing the CRP national cap to 15 million ha would increase the number of apiaries that meet key forage requirements by 68–210% in North Dakota and South Dakota. In turn, colonies within these apiaries would contribute to honey production, a $300 million USD agricultural product, and provide pollination services for a variety of fruits, vegetables, and other crops elsewhere in the country (41). For example, Smart et al. (21) showed that honey bee colonies in North Dakota surrounded by more grasslands had higher survival rates than colonies in landscapes with less conservation cover when transported to California to pollinate almonds, a pollinator-dependent crop worth over $5 billion USD annually. Our current research, in tandem with past studies, suggests that providing habitat for honey bees through the CRP will have a positive impact on pollinator health and, in turn, support agroecosystems and contribute to a healthy human diet elsewhere in the country. Our work provides a cogent example of the positive off-site benefits provided by the CRP to members of society who may never encounter or live near CRP-enrolled lands. Although policy debates often focus on the monetary cost of government-supported conservation programs, we highlight here how the CRP can be beneficial to pollinators, beekeepers, landowners, agricultural producers, and consumers alike.

By extension, perennial grassland also benefits biodiversity, including native pollinators and wildlife, and provides a variety of ecosystem services to both landowners and society (42). Producers and landowners can benefit from establishing perennial covers that include floral sources for honey bees because these lands reduce water runoff, increase soil retention, sequester soil nutrients, and support crop pest predators (43). The services provided by the CRP in some areas of the Midwest exceed the cost payments of the federal government to landowners (11). Therefore, the potential total benefits of adding CRP acreage could go far beyond what we have quantified in this study. An integrated modeling approach that couples economic land-use modeling with biological and ecological assessments is needed to evaluate tradeoffs in ecosystem services brought on by land-use change, agricultural policy, and the CRP.

Our model results also highlight how the spatial allocation of future CRP enrollments can be optimized to provide maximum forage value, as opposed to a random allocation of the same area of CRP land on the landscape. Strategic placement of CRP land would require significant cooperation between landowners, beekeepers, and US Department of Agriculture (USDA) staff to target areas where habitat for bees has been depleted but still retains a high density of apiaries. Similarly, our strategic reduction scenario shows how a reduced CRP national cap could be implemented to ameliorate, but not totally eliminate, the negative effects of CRP loss on honey bee landscape suitability. Our models can be used to identify high priority areas to establish new CRP enrollments, maintain current enrollments, or maximize pollinator benefits. Traditionally, CRP enrollments have targeted environmentally sensitive lands that are at risk for soil erosion or lands that exist within the core range of imperiled wildlife species. Thus, there is a precedent for enrolling private lands in the CRP that maximize particular ecosystem service benefits. However, current ranking criteria for landowner enrollments in the CRP do not reflect pollinator habitat value to a meaningful degree (44). Here, we show that strategic CRP enrollments in areas of high apiary density can maximize the benefits of the CRP to managed pollinators and contribute substantially to conservation goals established by the PHTF. Our study highlights how conservation initiatives, such as the CRP's Honey Bee Habitat Initiative (45), can be optimized to benefit pollinators. Additional CRP acreage would likely serve all three goals established by the PHTF by increasing pollinator habitat, establishing forage areas for monarch butterflies, and bolstering annual survival of honey bees. Furthermore, with the same national cap, the strategic enrollment policy does not necessarily increase the overall government budget, thus significantly improving the overall economic efficiency of the CRP. Our analysis assumed that all CRP enrollments provide a similar benefit to pollinators, an assumption unlikely to hold true considering the multiple practices and seed mix options that exist for CRP lands. In this light, our scenarios could be further extended by considering different CRP practices, and seeding mix options (23), to model their differential benefit to pollinators. Elevating the forage quality of CRP lands would likely benefit pollinators, independent of the national cap size.

Our analysis revealed a need for, and benefits from, the CRP in supporting honey bees, a species that provides an ecosystem service valued at $12 billion USD annually (4). Honey bee colonies that spend the summer in the NGP are subsequently transported around the country to pollinate multiple agricultural crops. Given the importance of honey bees to US agriculture and food security, our study shows how national policy that influences land-use decisions in the NGP can impact pollinator forage, with potential downstream consequences for US agriculture. Our CRP scenarios demonstrate how increasing the national CRP cap could have a measurable positive impact on pollinator habitat and, by extension, benefit the rest of society requiring healthy honey bees for crop pollination.

Methods

CRP Trends Around Apiaries. We developed a map to illustrate changes in CRP area within 1.6 km (~1.0 mile, primary foraging distance of honey bees) of 18,363 registered apiary locations in North Dakota and South Dakota from 2006 to 2016. Apiary registration locations in the PPR and elsewhere (*SI Appendix*, Fig. S1) were provided by the North Dakota and South Dakota Departments of Agriculture, and maps of annual CRP data were provided by the USDA Farm Service Agency through a data-sharing agreement. Data on CRP enrollments were available as digitized polygons for 2006, 2008 (North Dakota only), and 2009 through 2016. Due to data omissions, we did not include CRP data for Coddington County (South Dakota) in 2006 or Marshall County (South Dakota) in 2009. We used a geographic information system (GIS) to generate a 1.6-km buffer around each registered apiary point and quantified annual CRP area within the buffer. We created maps representing the density of changes in CRP area around apiaries using inverse distance weighting interpolation in a GIS. We then constructed a linear trend model with R (46) to estimate annual rate of change of CRP area around registered apiary locations. We calculated an average annual area of the CRP for all 18,363 apiary points and used this statistical average value as the response variable in our linear trend model. We report regression coefficients and 95% confidence intervals to evaluate statistical significance and effect size. We provide the area of various CRP conservation practices that existed within 1.6 km of apiaries in 2006 (*SI Appendix*, Fig. S3).

CRP Conversion. We estimated annual conversion rates of CRP fields within forage distance (1.6 km, as above) to registered apiary locations. We used land-cover data from the 2006 CDL as our baseline year to compare with CDL maps for 2007–2016 to track types and rates of conversion (details are provided in *SI Appendix*). Inferring rates of land-cover conversion from remotely sensed data can be difficult, as rates of annual misclassification can exceed rates of change in agricultural landscapes (47). We reduced the influence of potential mapping errors on our analysis of the conversion of CRP fields to cropland by recognizing such conversions only when field polygons remained in crop cover for a minimum of five consecutive years. We tracked whether CRP fields were converted to cropland (per our 5-y criterion); the year of conversion; and whether the initial crop type was corn, soybeans, or some other type. A caveat to our approach was that for 2013–2016, we lacked a full complement of five subsequent years to screen for potential mapping errors. Annual results after 2012 therefore may increasingly be influenced by mapping errors, especially for 2016, for which we had no subsequent data.

CRP Changes and Apiary Density. We quantified the number of registered apiaries and change in CRP area from 2006 to 2016 per township ($n = 4{,}563$) in North Dakota and South Dakota to investigate correlations of CRP area change with density of registered apiaries. We used townships as our unit of inference because they typically are a standard size (93 km^2, 36 mi^2) in North Dakota and South Dakota. Before analysis, we removed 919 townships with an area <90.6 km^2 (35 mi^2). Within each township, we calculated hectares of CRP area gained or lost from 2006 to 2016. Because apiaries per township, our response variable, consisted of count data, we applied a Poisson generalized linear model in program R (46) to relate the number of registered apiaries to gains and losses of CRP area within each township [linear predictor: $\log(\lambda_i) = \alpha + \beta_{\text{Region}} \times \text{Region} + \beta_{\Delta CRP} \times \Delta\text{CRP}$]. A significant and negative parameter estimate for $\beta_{\Delta CRP}$ would suggest that townships with higher apiary density experienced greater loss of CRP land.

Apiary Suitability and CRP Scenarios. For our scenario modeling, we considered multiple CRP national acreage caps that represent the plausible directions of future farm bill legislation. We treated the CRP land that existed in 2016, and the national acreage cap set by the 2014 Farm Bill (9.7 million ha, 24 million ac), as our baseline from which to compare our other CRP scenarios. Although we avoided an evaluation of specific acreage caps proposed by particular senators, representatives, and nongovernmental organizations (NGOs), we designed our scenarios with limits that reflected past CRP caps or caps that have been proposed by NGOs or policy makers:

i) 7.7 million ha (19 million ac) national cap: This scenario represented a 21% decrease in national CRP area relative to the 2016 acre cap and was consistent with the observed downward trend in CRP area, based on the limits imposed by the 2008 (12.9 million ha) and 2014 (9.7 million ha) US Farm Bills, respectively (48).

ii) 7.7 million ha (19 million ac) national cap with strategic reduction: Here, we considered a 21% decrease in CRP lands, where CRP enrollments located within 3.2 km of registered apiaries were preferentially maintained to maximize forage benefit to honey bees, whereas CRP enrollments beyond this distance were allowed to expire. This scenario represented a national reduction in CRP, while recognizing the value of CRP lands as pollinator habitat in the NGP.

iii) 15.0 million ha (37 million ac) national cap: This scenario represented a 54% increase in the CRP cap relative to the 2014 Farm Bill and was consistent with the historical maximum CRP enrollment cap established by the 2002 Farm Bill [15.9 million ha (48)] and similar to some acreage caps being proposed for the 2018 Farm Bill.

iv) 15.0 million ha (37 million ac) national cap with strategic placement: Here, we considered a 54% increase in CRP lands, with CRP acres strategically located within 3.2 km of registered apiaries to maximize forage benefit to honey bees. This scenario simulated a situation where establishing habitat for pollinators was given top priority for new CRP enrollments in the NGP.

To implement the scenarios spatially, we first reapportioned the national caps to North Dakota and South Dakota based on their observed 10-y high and low percentages of national CRP acreage (*SI Appendix*). For each scenario, the state caps were further reallocated to each county using its current percent of state CRP acreage.

We developed a map of cultivated lands to restrict the distribution of CRP gains to cropped areas in each county. We reclassified pixels from the CDL as either "cultivated" or "noncultivated" during 2011–2016, and then screened for those pixels that met the criterion of being cultivated in 4 of the 6 y (*sensu* ref. 49). To add or remove CRP polygons, we used polygon land units delineated by the USDA for tracking landowner participation in farm programs (https://www.fsa.usda.gov/programs-and-services/aerial-photography/imagery-products/common-land-unit-clu/index) and overlayed these land units with the map of cultivated areas to assign a cultivated or noncultivated label to each land unit.

We prioritized the addition or removal of CRP polygons in the landscape based on their level of capability to support crops [determined with the Land Capability Class (LCC) in the USDA Soil Survey Geographic database (https://www.nrcs.usda.gov/wps/portal/nrcs/detail/soils/survey/geo/?cid=nrcs142p2_053627)]. To meet the 15.0-million ha alternative cap, we converted cultivated land units with the poorest available LCC ratings to new CRP enrollments. Conversely, to meet the 7.7-million-ha alternative cap, we removed CRP polygons from cultivated land units with the best available LLC ratings. For the 7.7-million-ha strategic reduction scenario, we preferentially maintained current CRP enrollments within 3.2 km of apiaries and allowed CRP enrollments beyond this distance to expire (*SI Appendix*). For the 15.0-million-ha strategic planning scenario, we prioritized placement of new CRP polygons within proximity to registered apiary sites to maximize the forage potential for honey bees.

We determined the number of apiaries that could be supported by the surrounding CRP acres resulting from each scenario with forage criteria from three published studies: (*i*) 380 ha of CRP land within 3.2 km (2 miles) of an apiary (21), (*ii*) 210 ha of CRP land within 1.6 km (1 mile) of an apiary (20), and (*iii*) 130 ha of CRP land within 3.2 km (2 miles) of an apiary (12). Note that the CRP criteria from these studies represented only partial land-cover criteria for supporting honey bee colonies. Additional scenario details can be found in *SI Appendix*.

Our analyses are representative of typical commercial apiaries in North Dakota and South Dakota, both in terms of number of colonies [48 colonies per apiary (21)] and colony size (40,000 bees per colony), and unrepresentative of hobby apiaries, exceptionally large apiaries, or temporary holding yards. We archived all nonproprietary data and metadata associated with this study in the US Geological Survey ScienceBase-Catalog (50).

ACKNOWLEDGMENTS. We thank Alec Lawton, Stefano Potter, and Ning Li for GIS assistance and Mace Vaughan, Wes Newton, and two anonymous reviewers for their constructive comments. This work was supported by the USDA Farm Service Agency (Inter Agency Agreement 16IAMRECRPHBTA1), National Science Foundation (NSF) Experimental Program to Stimulate Competitive Research (Grant IIA-1355466), the USDA National Institute of Food and Agriculture (Grant 2015-67020-23175), and US Geological Survey Ecosystems Mission Area. Any use of trade, firm, or product names is for descriptive purposes only and does not imply endorsement by the US Government.

1. Klein A-M, et al. (2007) Importance of pollinators in changing landscapes for world crops. *Proc Biol Sci* 274:303–313.
2. Ollerton J, Winfree R, Tarrant S (2011) How many flowering plants are pollinated by animals? *Oikos* 120:321–326.
3. Potts SG, et al. (2010) Global pollinator declines: Trends, impacts and drivers. *Trends Ecol Evol* 25:345–353.
4. Calderone NW (2012) Insect pollinated crops, insect pollinators and US agriculture: Trend analysis of aggregate data for the period 1992-2009. *PLoS One* 7:e37235.
5. Lee KV, et al. (2015) A national survey of managed honey bee 2013–2014 annual colony losses in the USA. *Apidologie (Celle)* 46:292–305.
6. Koh I, et al. (2016) Modeling the status, trends, and impacts of wild bee abundance in the United States. *Proc Natl Acad Sci USA* 113:140–145.
7. Semmens BX, et al. (2016) Quasi-extinction risk and population targets for the Eastern, migratory population of monarch butterflies (Danaus plexippus). *Sci Rep* 6:23265.
8. Goulson D, Nicholls E, Botías C, Rotheray EL (2015) Bee declines driven by combined stress from parasites, pesticides, and lack of flowers. *Science* 347:1255957.
9. Spivak M, et al. (2017) Why does bee health matter? The science surrounding honey bee health concerns and what we can do about it (Council for Agricultural Science and Technology, Ames, IA), QTA2017-1.
10. Gelfand I, et al. (2011) Carbon debt of Conservation Reserve Program (CRP) grasslands converted to bioenergy production. *Proc Natl Acad Sci USA* 108:13864–13869.
11. Johnson KA, et al. (2016) Conservation Reserve Program (CRP) lands provide ecosystem service benefits that exceed land rental payment costs. *Ecosyst Serv* 18:175–185.
12. Gallant AL, Euliss NH, Jr, Browning Z (2014) Mapping large-area landscape suitability for honey bees to assess the influence of land-use change on sustainability of national pollination services. *PLoS One* 9:e99268.
13. Euliss NH, Jr, et al. (2011) Integrating estimates of ecosystem services from conservation programs and practices into models for decision makers. *Ecol Appl* 21(Suppl 1):S128–S134.
14. Morefield PE, LeDuc SD, Clark CM, Iovanna R (2016) Grasslands, wetlands, and agriculture: The fate of land expiring from the Conservation Reserve Program in the Midwestern United States. *Environ Res Lett* 11:094005.
15. US Department of Agriculture National Agricultural Statistics Service (2002) Honey Report: 2002. Available at http://usda.mannlib.cornell.edu/usda/nass/Hone//2000s/2002/Hone-02-28-2002.pdf. Accessed June 14, 2018.
16. US Department of Agriculture National Agricultural Statistics Service (2006) Honey Report: 2006. Available at http://usda.mannlib.cornell.edu/usda/nass/Hone//2000s/2006/Hone-02-28-2006.pdf. Accessed June 14, 2018.
17. US Department of Agriculture National Agricultural Statistics Service (2008) Honey Report: 2008. Available at http://usda.mannlib.cornell.edu/usda/nass/Hone//2000s/2008/Hone-02-29-2008.pdf. Accessed June 14, 2018.
18. US Department of Agriculture National Agricultural Statistics Service (2017) Honey Report: 2017. Available at http://usda.mannlib.cornell.edu/usda/nass/Hone//2010s/2017/Hone-03-22-2017.pdf. Accessed June 14, 2018.
19. Delaplane KS, Mayer DF (2000) *Crop Pollination by Bees* (CABI Publishing, New York).
20. Otto CR, Roth CL, Carlson BL, Smart MD (2016) Land-use change reduces habitat suitability for supporting managed honey bee colonies in the Northern Great Plains. *Proc Natl Acad Sci USA* 113:10430–10435.
21. Smart MD, Pettis JS, Euliss NH, Jr, Spivak M (2016) Land use in the Northern Great Plains region of the U.S. influences the survival and productivity of honey bee colonies. *Agric Ecosyst Environ* 230:139–149.
22. California Department of Food and Agriculture (2016) California Agricultural Statistics Review, 2015–2016. Available at https://www.cdfa.ca.gov/statistics/PDFs/2016Report.pdf. Accessed October 1, 2017.
23. Otto CRV, et al. (2017) Using publicly available data to quantify plant–pollinator interactions and evaluate conservation seeding mixes in the Northern Great Plains. *Environ Entomol* 46:565–578.
24. Lark TJ, Salmon JM, Gibbs HK (2015) Cropland expansion outpaces agricultural and biofuel policies in the United States. *Environ Res Lett* 10:044003.
25. Hellerstein D, Malcolm S (2011) The influence of rising commodity prices on the Conservation Reserve Program (US Department of Agriculture, Economic Research Service, Washington, DC), Economic Research Report 110.
26. Claassen R, Carriazo F, Cooper J, Hellerstein D, Ueda K (2011) Grassland to cropland conversion in the Northern Plains: The role of crop insurance, commodity, and disaster programs (US Department of Agriculture, Economic Research Service, Washington, DC), Economic Research Report 120.
27. US Department of Agriculture National Agricultural Statistics Service (2018) Crop production historical track records. Available at www.nass.usda.gov/Publications. Accessed May 21, 2018.
28. Henry M, et al. (2012) A common pesticide decreases foraging success and survival in honey bees. *Science* 336:348–350.
29. Girolami V, et al. (2009) Translocation of neonicotinoid insecticides from coated seeds to seedling guttation drops: A novel way of intoxication for bees. *J Econ Entomol* 102:1808–1815.
30. Mogren CL, Lundgren JG (2016) Neonicotinoid-contaminated pollinator strips adjacent to cropland reduce honey bee nutritional status. *Sci Rep* 6:29608.
31. Douglas MR, Tooker JF (2015) Large-scale deployment of seed treatments has driven rapid increase in use of neonicotinoid insecticides and preemptive pest management in US field crops. *Environ Sci Technol* 49:5088–5097.
32. Stanley DA, et al. (2015) Neonicotinoid pesticide exposure impairs crop pollination services provided by bumblebees. *Nature* 528:548–550.
33. Wu-Smart J, Spivak M (2016) Sub-lethal effects of dietary neonicotinoid insecticide exposure on honey bee queen fecundity and colony development. *Sci Rep* 6:32108.
34. Krupke CH, Hunt GJ, Eitzer BD, Andino G, Given K (2012) Multiple routes of pesticide exposure for honey bees living near agricultural fields. *PLoS One* 7:e29268.
35. Smart M, Pettis J, Rice N, Browning Z, Spivak M (2016) Linking measures of colony and individual honey bee health to survival among apiaries exposed to varying agricultural land use. *PLoS One* 11:e0152685.
36. Johnson DH, Igl LD (1995) Contributions of the Conservation Reserve Program to populations of breeding birds in North Dakota. *Wilson Bull* 107:709–718.
37. Gebhart DL, Johnson HB, Mayeux H, Polley H (1994) The CRP increases soil organic carbon. *J Soil Water Conserv* 49:488–492.
38. Evans JD, Spivak M (2010) Socialized medicine: Individual and communal disease barriers in honey bees. *J Invertebr Pathol* 103(Suppl 1):S62–S72.
39. Cane JH, Tepedino VJ (2017) Gauging the effect of honey bee pollen collection on native bee communities. *Conserv Lett* 10:205–210.
40. Herbertsson L, Lindström SAM, Rundlöf M, Bommarco R, Smith HG (2016) Competition between managed honeybees and wild bumblebees depends on landscape context. *Basic Appl Ecol* 17:609–616.
41. Hellerstein D, Hitaj C, Smith D, Davis A (2017) Land use, land cover, and pollinator health: A review and trend analysis (US Department of Agriculture, Economic Research Service, Washington, DC), Economic Research Report 232.
42. Werling BP, et al. (2014) Perennial grasslands enhance biodiversity and multiple ecosystem services in bioenergy landscapes. *Proc Natl Acad Sci USA* 111:1652–1657.
43. Landis DA, et al. (2017) Biomass and biofuel crop effects on biodiversity and ecosystem services in the North Central US. *Biomass Bioenergy*, 10.1016/j.biombioe.2017.02.003.
44. Iovanna R, et al. (2017) Assessing pollinator habitat services to optimize conservation programs. *The Valuation of Ecosystem Services from Farms and Forests*, eds Waigner L, Ervin D (The Council on Food, Agricultural and Resource Economics, Washington, DC), pp 1–27.
45. US Department of Agriculture Farm Service Agency (2015) Conservation Reserve Program honey bee habitat initiative. Available at https://www.fsa.usda.gov/Assets/USDA-FSA-Public/usdafiles/FactSheets/2015/CRPProgramsandInitiatives/Honey_Bee_Habitat_Initiative.pdf. Accessed September 1, 2017.
46. R Core Team (2014) R: A Language and Environment for Statistical Computing (R Foundation for Statistical Computing, Vienna). Available at www.R-project.org/. Accessed May 1, 2017.
47. Reitsma KD, Clay DE, Clay SA, Dunn BH, Reese C (2016) Does the US cropland data layer provide an accurate benchmark for land-use change estimates? *Agron J* 108:266–272.
48. Stubbs M (2014) Conservation Reserve Program (CRP): Status and issues (Congressional Research Service, Washington, DC), Report 42783, p 24.
49. US Department of Agriculture National Agricultural Statistics Service (2017) National 2016 cultivated layer. Available at https://nassgeodata.gmu.edu/CropScape/. Accessed August 1, 2017.
50. Otto CRV (2018) Pollinators in the Great Plains: The Past Role and Future Outlook of the Conservation Reserve Program in Supporting Honey Bees, Datasets. US Geological Survey Data Release, 10.5066/F7FQ9VW9.