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Feeling the sting? Addressing land-use changes can mitigate bee declines

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ABSTRACT

Pollinators are an essential component of functioning and sustainable agroecosystems. Despite their critical economic and ecological role, wild and managed bees are declining throughout the United States and across the globe. Commercial beekeepers lost nearly 40.5% of their colonies in 2015–2016 and estimated wild bee abundance declined 23% between 2008 and 2013. These losses are due to a number of factors—including parasites, pesticides, and pathogens—but one key driver is the loss of habitat and floral resources necessary for pollinator survival. Here, we trace how land-use changes, and the policies and land management practices behind them, have played a role in diminishing floral resources and provide steps that can be taken to mitigate forage and habitat loss due to land-use changes. By addressing land-use changes and their drivers, considerable progress can be made toward mitigating bee declines and achieving national goals for pollinator health.

Wild and managed bees are declining throughout the United States and across the globe. Commercial beekeepers lost 40.5% of their colonies between April 2015 and 2016 (Kulhanek et al., 2017), and estimated wild bee abundance declined 23% between 2008 and 2013 (Koh et al., 2016). Pollinator losses are not simply a national phenomenon, but part of a global trend of insect biodiversity decline. A recent report on global insect declines argued that current trends point to the extinction of 40% of the world's insect species over the next few decades (Sánchez-Bayo and Wyckhuys, 2019). Hymenoptera—the order of insects comprising wasps, ants, and bees—were among the insects most affected.

Wild and managed bee losses are due to multiple drivers, including parasites such as *Varroa* mites, pathogen and disease, pesticides, reduced floral resources, and the loss of nesting and foraging habitat (Goulson et al., 2015). The latter of these, habitat loss, is the number one global driver of reduced insect biodiversity, followed by agrochemical pollution (Sánchez-Bayo and Wyckhuys, 2019). Pollinator losses are both ecologically and economically problematic, given that bees and other insect pollinators are an essential component of functioning and sustainable agroecosystems. Insect pollination, for example, adds an estimated $15 billion annually in direct pollination services to food crops in the United States (Calderone, 2012).

In this viewpoint, we identify how policies and land management practices over the past 15 years have had unintended negative effects on habitat and forage for managed and wild bees in the U.S. Midwest, a region critically important for honey bees and wild pollinators. Although drivers of land-use changes are often difficult to identify, we use published literature to highlight the main political and economic factors that have influenced land-use and land-management decisions made by landowners and agricultural producers, such as agricultural policies, crop insurance programs, and a shift towards prophylactic pesticide use with neonicotinoid-treated seeds. We also summarize some of the existing findings on the effects of land-use changes on bee health that we used to formulate this article (Appendix Table A1).

Through this investigation, we hope to demonstrate not only how land-use changes play a central role in the loss of bee habitat, but also argue that altering the current state of land-use change—and the policies that drive them—can help mitigate bee losses as well. Based on the best available science, we highlight steps that can be taken to mitigate forage and habitat loss due to land-use change, such as increasing acreage and support for pollinator habitat, reducing pesticides on row crops through integrated pest management (IPM) practices, and creating a national native pollinator monitoring system to track wild bee population trends. Identifying the policies and land management practices that negatively affect pollinators will provide valuable insight to practitioners, policy makers, and organizations working to achieve national goals for improving pollinator health (Pollinator Health Task Force, 2015).

1. Crucial bee forage in the Midwest Prairie

A key area to illustrate the impact of land-use change on bee habitat is the Prairie Pothole Region (PPR) in the Midwestern United States (Fig. 1). The PPR has a unique geography comprised of depressional

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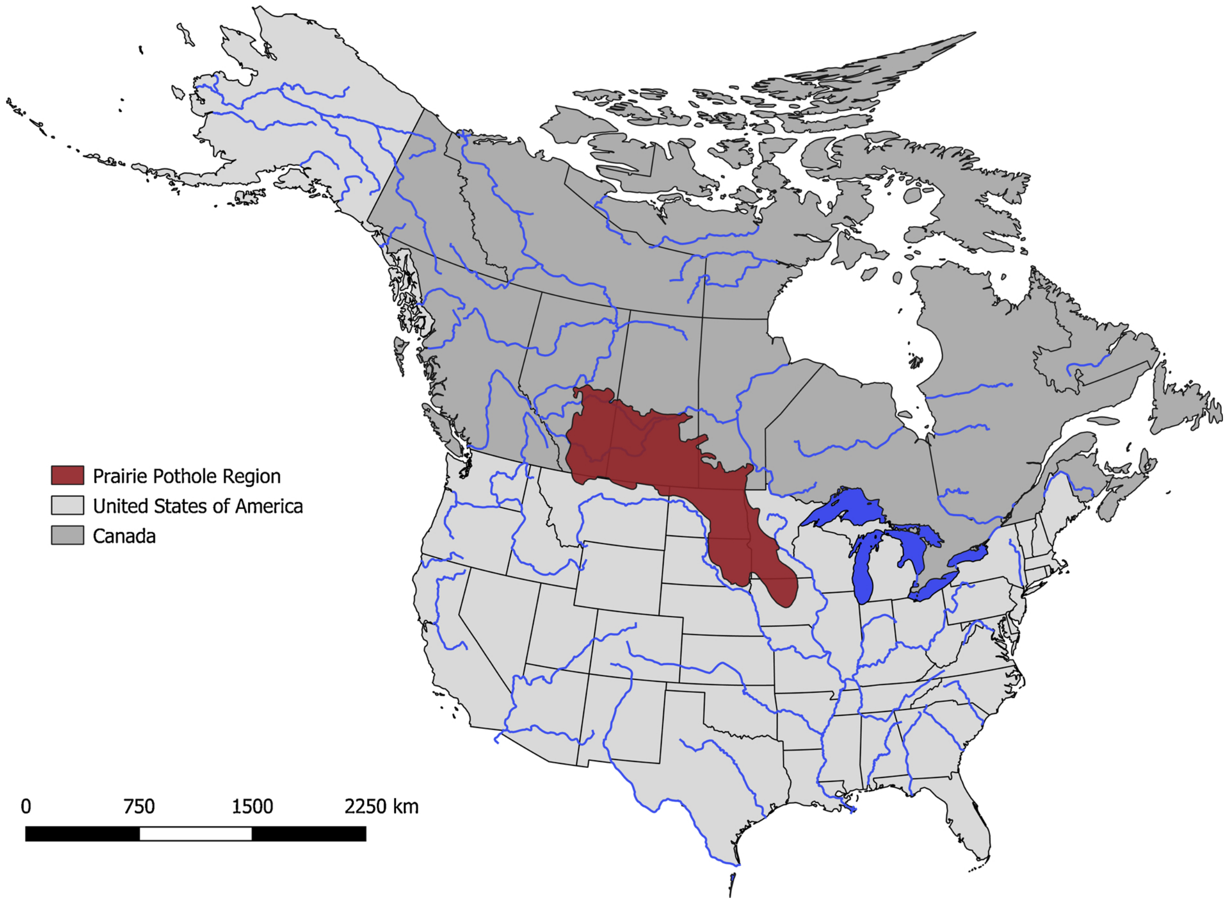

Fig. 1. A map of the Prairie Pothole Region in the United States and Canada.

wetlands (i.e., potholes) and varied grasslands embedded within an agricultural matrix spanning three Canadian provinces, as well as Minnesota, Iowa, North and South Dakota, and Montana in the U.S. Because of this unique geography, the PPR provides an ideal waterfowl breeding habitat (Johnson et al., 2005) and is home to species such as monarch butterflies, amphibians, and other migratory birds.

The PPR is also one of the most important parts of the United States for honey production, bee health, and pollination services (Hellerstein et al., 2017). Each spring and summer, beekeepers truck nearly 40% of the nation's commercially managed honey bees to the PPR (Otto et al., 2016). Summer locations used by beekeepers in the PPR provide a safe-haven for honey bee colonies and directly influence overwintering survival and bee nutrition (Smart et al., 2016a). In the PPR, honey bees forage on alfalfa, canola, sunflowers, and wildflowers growing on native and established grasslands such as those enrolled in the Conservation Reserve Program (CRP). States in the PPR support the highest density of honey bee colonies in the nation and are often the top producers of honey (Hellerstein et al., 2017).

One of the reasons the PPR is a keystone for wildlife and beekeeper livelihood is the existence of the CRP, a voluntary program administered through the Farm Service Agency under the United States Department of Agriculture (USDA). Established in the 1985 Farm Bill, the CRP pays an annual rental fee to landowners to remove marginal farmland from crop production for the establishment of perennial cover, typically in the form of a grassland. As of 2018, around 22.7 million acres of land were enrolled in the CRP nationwide (USDA, 2018), with a designated funding of $2 billion annually (Stubbs, 2014). The benefits of CRP land include improved soil health, wildlife habitat, water quality, and carbon sequestration (Gleason et al., 2011; Morefield et al., 2016).

The CRP has also helped maintain forage sites for commercial beekeepers (Hellerstein et al., 2017), who largely do not own the land they need for honey production, but rather, rely almost entirely on contractual arrangements with landowners (Durant, 2019). CRP land is attractive to beekeepers for honey production partly because landowners are restricted in their ability to hay and graze the land, so beneficial flowering plants can bloom and provide nutritious resources to bees throughout the growing season (Otto et al., 2016; Smart et al., 2016b). Otto et al. (2018) estimated that over 3000 apiary locations in North and South Dakota met or exceeded the critical foraging requirement of honey bee colonies based on the existence of CRP land alone. Commercial beekeepers place their honey bee colonies in close proximity to CRP land because these fields host a variety of forage plants throughout the growing season. A spatially explicit landscape model developed by Gallant et al. (2014) suggested that ≥130 ha (321 acres) of CRP land or comparable grasslands was needed to support apiaries containing 100 honey bee colonies.

CRP land and native grasslands are not only a necessity for commercial beekeepers, they play a crucial role in supporting bee health. In one study, honey bee colonies located in close proximity to CRP fields had heightened levels of colony health metrics including vitellogenin—a protein that affects bee immune system function and behavioral maturation (Ricigliano et al., 2019). Smart et al. (2018) showed that honey bee colonies placed in grassland landscapes in the PPR grew more rapidly and maintained a larger population size into the winter. These larger bee colonies generated additional beekeeper revenue the subsequent spring during almond pollination. Although less studied, wild bees also benefit from CRP plantings in the PPR (Evans et al., 2018). Wild bees not only gather pollen and nectar from forbs growing on CRP land and other grasslands (Otto et al., 2017), they also use the undisturbed soil and hollow grass stems for nesting. Wild bee abundance can be two to three times greater in grassland than soybean or corn fields (Gardiner et al., 2010).

2. Land-use changes result in forage loss

In the PPR, CRP lands and native grasslands are disappearing, largely due to weakened conservation funding in recent U.S. Farm Bills and biofuel mandates (Morefield et al., 2016, p. 2), crop insurance (Claassen et al., 2011), and record high prices for commodity crops during 2008–2013 (Rashford et al., 2010; Wright and Wimberly, 2013). Between 2010 and 2013, nearly 30% of land (530,000 ha, 1.3 million acres) previously enrolled in the CRP in 12 Midwestern states was primarily converted to corn or soybeans (Morefield et al., 2016); crops that are increasingly grown as feedstocks for production of ethanol and bio-diesel, respectively. Among the states encompassing the PPR, 4.9 million ha (12.2 million acres) were enrolled in the CRP in 2007, but by 2017, enrolled acreage had declined by nearly half to 2.7 ha (6.8 million acres) (Fig. 2) (USDA-FSA, 2019). Notably, the highest rate of grassland conversion to cropland in the PPR took place in areas within 100 miles of corn ethanol refineries from 2008 to 2012 (Wright et al. 2017).

Conversion of grassland to corn or soybeans in the PPR replaces valuable bee forage and habitat with monoculture crops that have little nutritional value to bees, thereby reducing forage quality of the landscape (Hellerstein et al., 2017). Although CRP land has diminished throughout the U.S., some of the most drastic losses have been in the PPR, in close proximity to prime beekeeping areas (Hellerstein et al., 2017; Otto et al., 2018).

Several policies likely incentivized conversion of CRP land and native grassland to cropland. One of the most influential was the Renewable Fuel Standard, which was authorized under the 2005 Energy Policy Act and then expanded under the 2007 Energy Independence and Security Act (US Congress, 2007). The Renewable

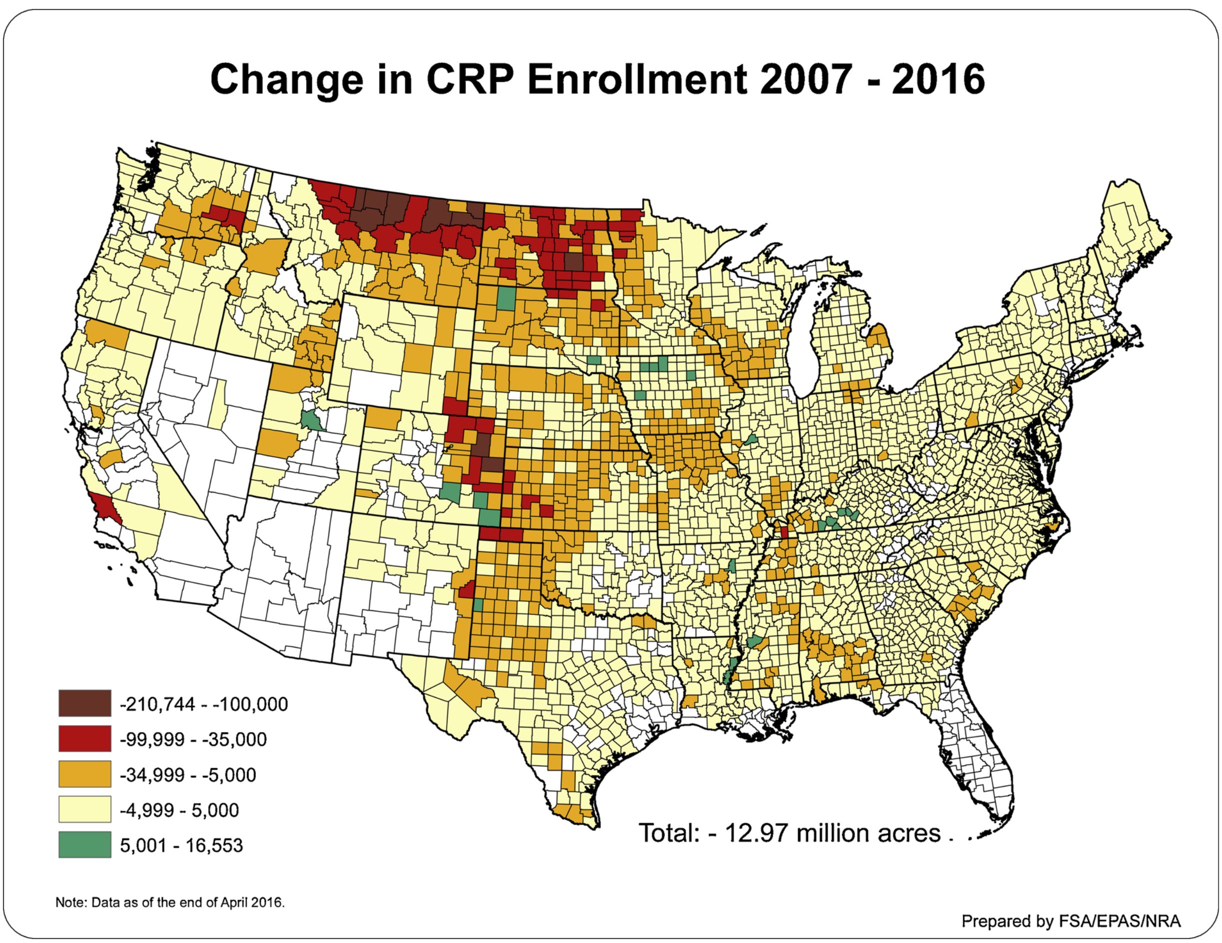

Fig. 2. Change in Conservation Reserve Program acreage by county throughout the U.S. from 2006 to 2017 (USDA-FSA, 2016). There was a loss of -12.97 million acres of CRP lands nationally during this time period.

Fuel Standard's ethanol mandate aimed to expand the nation's renewable fuel sector, cut greenhouse gas emissions, and reduce reliance on oil imports by requiring an annually increasing percentage of ethanol and biofuels to be mixed with petroleum-based transportation fuel (US Congress, 2007). As of 2018, the Renewable Fuel Standard mandated the annual production of 73 billion liters (19.3 billion gallons) of renewable biofuels, mostly corn-based ethanol (US EPA, 2017).

According to USDA statistics, shortly after these policies were enacted, corn commodity prices rose from around $2 per bushel in 2006 to $7 per bushel in 2013 (USDA-NASS, 2015).(Soy also increased from $5 per bushel in 2006 to $15 per bushel in 2013. High commodity prices during 2008–2013 made it economically profitable to convert CRP grassland and native grassland to row crops. Many farmers terminated their CRP contract or did not re-enroll in the CRP after their contract expired (Stubbs, 2014). The 2014 Farm Bill also reduced the CRP enrollment cap from 32 million acres to 24 million acres by 2018—a 25% decrease in available CRP acreage (Stubbs, 2014). Commodity crop prices have since declined from these historical highs, to $3 and $9 per bushel in 2018 for corn and soy, respectively (USDA-NASS, 2018a), thereby making CRP rental payments more competitive. However, since CRP acreage was enrolled to its maximum of 24 million acres, new participation in the CRP was not possible for producers until the implementation of the 2018 Farm Bill, which increased the CRP national cap to 27 million acres nationally by 2023.

Crop insurance programs also incentivized farmers to shift into crop production (Claassen et al., 2011). Though direct payments for corn and soy were repealed in the 2014 Farm Bill, the bill expanded payments into two new programs, Price Loss Coverage and Agricultural Risk Coverage, which allowed farmers to receive payments if revenue from commodity crops dropped below a price-point benchmark (Stubbs, 2014). These programs are valuable and provide an important safety net for farmers facing weather-related disasters. However, these programs can have unintended, negative consequences on bee habitat, particularly on marginal lands. For example, crop insurance, marketing loans, and disaster payments increased conversion of 686,000 acres of working grasslands, such as pasture and hay, and CRP lands to crop production between 1998 and 2007 (Claassen et al., 2011).

It is not simply diminishing forage that challenges honey bee and wild bees in the PPR, but also the insecticides that accompany corn and soy plantings (van der Sluijs et al., 2015). Neonicotinoids, now the most commonly used class of insecticide across the globe (Sparks, 2013), have been rapidly adopted by U.S. producers to control insect crop pests. Neonicotinoids are currently used on nearly 100% of all corn crops and between 34–44% of soy crops in the United States (Douglas and Tooker, 2015), totaling around 110 out of 171.4 million acres of corn and soy (USDA-NASS, 2018b). Continued expansion of corn and soy throughout the Midwest increases honey bees' and wild bees' exposure risk to neonicotinoids—all of which have documented lethal and sub-lethal effects on honey bees and wild pollinators (Goulson, 2013).

Bees can be exposed to neonicotinoids through multiple pathways including contacting contaminated dust clouds during crop planting, field sprays drifting to adjacent wildflower patches or apiaries, or through systemic uptake by untreated wildflowers adjacent to the crop field. Bees can be exposed to neonicotinoids while collecting pollen and nectar from wildflowers that have become contaminated by neonicotinoid residues blowing across farm fields and into adjacent wildflower patches (Botías et al., 2015; Main et al., 2014). Orally ingesting the dust produced during spring seed plantings can be acutely toxic to honey bees, contributing to increased worker bee mortality and queen failure over time (Tsvetkov et al., 2017), and reduced colony growth and queen performance in bumblebees (Whitehorn et al., 2012).

One two-year study showed that honey bee colonies located near a corn-growing area had 3.5 times higher mortality rates than colonies from corn-free sites (Samson-Robert et al., 2017). While these bees were exposed to a number of agrochemicals, they were primarily exposed to neonicotinoid compounds. Heightened exposure risk during planting season has caused many beekeepers to delay transporting their colonies into the PPR until after corn and soybean are seeded (Durant, 2019). This delay in colony transportation to the PPR can result in lost revenue for beekeepers who miss out on spring honey production and must supplement their colonies with synthetic food sources to keep them from starving in the spring.

Neonicotinoids are often applied directly to corn and soybean seeds prior to planting, which has led to the prophylactic use of insecticides on large-scale farms. This conflicts with key principles of IPM (Tooker et al., 2017), a system developed to adaptively manage pest populations if and when they occur, as opposed to the preemptive approach adopted when applying neonicotinoid seed treatments. Given the near ubiquitous availability of neonicotinoid seed treatments on commodity crops, producers have few options to buy untreated seed from local seed vendors (Tooker et al., 2017). Thus, producers are often obligated to use, and pay for, neonicotinoid seed treatments despite research indicating that treated seeds decrease beneficial insect predator populations, which can actually *diminish* crop yields (Douglas et al., 2015). In one three-year study, field experiments failed to demonstrate any significant yield benefits from planting seed-treated corn (Krupke et al., 2017), paralleling findings that indicate inconsistent or no yield benefits from planting treated oilseed rape in England and Wales (Budge et al., 2015) and soybeans in the U.S. (Seagraves and Lundgren, 2012). While neonicotinoids have undeniable benefits in controlling unwanted insect pests, these studies suggest that the ecological costs of planting these treated seeds warrant more judicial application.

3. Improve bee health through increased habitat and monitoring

Policy makers and land managers can use multiple mechanisms to improve pollinator habitat and achieve the national goal of restoring seven million acres of pollinator habitat by 2020 (Pollinator Health Task Force, 2015). The USDA offers several opportunities through the CRP and the Environmental Quality Incentives Program to improve the cost-effectiveness of marginal farmland while also supporting pollinator habitat; however, as we have demonstrated, these programs can come into conflict with policies and programs driving corn and soybean production such as biofuel mandates and crop insurance programs.

A number of actions can be taken to counter recent land-use changes and increase forage acreage for wild and honey bees. Congress recently increased CRP acreage by 12.5% in 2018 from 24 to 27 million acres by 2023, suggesting an increased societal interest in the CRP during periods of decreased commodity crop prices. Increasing the national CRP cap still further would improve landscape suitability for supporting the commercial beekeeping industry (Otto et al., 2018). In addition, economic sanctions can discourage the conversion of environmentally sensitive marginal land into row crop production. Currently, crop insurance programs provide an economic buffer against the risk of converting marginal lands into row crop production (Claassen et al., 2011), thus incentivizing land-use conversion.

To stem these conversions, Congress implemented the Sodsaver program in the 2014 Farm Bill, which reduced the crop insurance subsidies farmers could receive on lands converted to row crops from native sod for four years following the conversion (Lark et al., 2015). However, this provision only includes six states (North and South Dakota, Minnesota, Iowa, Montana, and Nebraska), reduces the insurance payment by just 50%, and only applies to native grasslands, and not wetlands, forests, or other native covers (Claassen et al., 2011; Lark et al., 2015). Analysts have suggested the Sodsaver's environmental compliance provisions could be strengthened to be more like the Swampbuster provision in the 1985 Farm Bill, which can be used to fully deny any farm payments (such as crop insurance) to producers who drain wetlands for crop production (Claassen et al., 2011, p. 48). Future Farm Bills could also expand the Sodsaver program beyond states in the PPR and implement the program nationwide (Lark et al., 2015).

Land-use decisions made by producers have a profound impact on the availability of pollinator habitat in working landscapes of the PPR. For example, producers can support bees by restoring unproductive row crop acres to perennial cover through the CRP or other conservation programs. Historically, most CRP fields in the PPR did not include diverse, native forb plantings for wild bees; however, the CRP now includes conservation practices that focus on wild bee habitat enhancement. Marginal areas within otherwise productive farmland (i.e., areas where crop production input costs may outweigh outputs) can be considered prime areas for pollinator enhancement. Not only will these plantings benefit honey bees, wild bees, and other wildlife (McConnell and Burger, 2016) they may also facilitate pollination services in adjacent farmland and improve the soil health when the land is returned to crop production (Karlen et al., 1999).

Producers can also help bees by shifting pesticide use practices. To reduce bee exposure, the application of neonicotinoids should be embedded within an IPM framework, rather than the insurance-based, prophylactic approach that has been widely adopted in recent years (Tooker et al., 2017). Using neonicotinoids within an IPM framework will increase their effectiveness when they are needed to control pest populations, while minimizing the unintended consequences of neonicotinoids on the environment and pollinators. Currently, producers have limited options for choosing to buy non-treated seeds for several commodity crops. Improving access to these seeds will provide the opportunity for producers to make choices that are economically profitable and environmentally sustainable for their farms.

In addition to increasing habitat and reducing the use of treated seeds, effective monitoring to track wild bee populations through time would help determine whether national goals for improving pollinator health have been achieved. In 2015, the Pollinator Health Task Force (2015) highlighted the need for national wild bee monitoring, but little progress has been made as of 2018. Honey bee annual losses are tracked by researchers (Kulhanek et al., 2017), but no such comparable monitoring program exists for wild bees (US GAO, 2016). In 2016, a national framework was developed for inventorying and monitoring wild bees on National Wildlife Refuges (Droege et al., 2016) and this framework has been sporadically adopted by some government agencies and researchers. However, unified sampling and data recording protocols, typical of other national monitoring programs for vertebrate wildlife, are lacking for wild bees. Evaluating the efficacy of national programs to improve wild bee health will be difficult to trace without a corresponding monitoring program.

One of the major hurdles for developing a national monitoring program for wild bees is the lack of taxonomic expertise needed to identify the estimated 4000 species of wild bees that exist in the U.S. Addressing these deficiencies in wild bee identification is a logical first step in creating a national monitoring program for wild bees. Additional resources could be dedicated to universities to support training of the next generation of bee taxonomists. Furthermore, strategic investment could be made to develop genetic techniques for identifying wild bees (Sing et al., 2016). Involving geneticists in wild bee identification would help address the national bottleneck that currently exists.

Based on the best available science, we have shown how land-use changes, and the political and economic drivers of these changes, have affected habitat for bees in a critical part of the country. We have also identified the absence of a national monitoring program for wild bees and have highlighted ways to address our national deficiency in wild bee identification expertise. In addition, we highlighted several key areas such as commodity insurance policy programs, CRP acreage caps, and prophylactic pesticide use that could be addressed to mitigate bee losses caused by land-use changes in the U.S. By reducing habitat loss and restoring pollinator habitat in agroecosystems, the carrying capacity for both wild bees and honey bees can be increased (Koh et al., 2016; Otto et al., 2018). Just as land-use decisions have resulted in decreased bee habitat in recent years, so too can actions be taken to improve bee habitat, with downstream benefits on agricultural productivity, ecosystem function, and human health.

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Competing interests

Authors declare no competing interests.

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Appendix A

Table A1
Studies that assessed pollinator response to grassland and grassland land-cover change.

Reference	Bee Group	Location	Study Type	Focus	Key Finding
Bennett and Isaacs (2014)	Wild Bees	Michigan, USA	Field	Wild bee abundance and diversity across a grassland gradient	Landscape composition, including grassland, had a significant effect on bee abundance and diversity.
Bennett et al. (2014)	Wild Bees	Michigan, USA	GIS	Bee response to bioenergy scenarios	Conversion of marginal farmland to perennial grasslands could increase bee abundance by 0 to 600%.
Dolezal et al. (2016)	Honey Bees	Iowa, USA	Field	Individual bee nutritional physiology in relation to land cover	Honey bees in areas of low cultivation exhibited higher lipid levels. Varroa mite infestation potentially obscures land use effects on bee health.
Evans et al. (2018)	Wild Bees and Honey Bees	North Dakota, USA	Field	Native bee abundance and diversity across land use gradient	Grasslands and other natural land covers were associated with increased bee diversity, abundance, and functional diversity.
Gallant et al. (2014)	Honey Bees	North Dakota, USA	GIS	Development of honey bee land-use model	Sites with ≥130 ha of conservation grasslands are a key criterion for supporting apiaries with 100 honey bee colonies.
Hellerstein et al. (2017)	Honey Bees	USA, national	GIS	Development of a pollinator forage suitability index	Nationally, forage suitability increased from 1982 to 2000, but declined from 2002 to 2012. Forage declines were most significant in important honey bee regions such as the Northern Great Plains.
Herbertsson et al. (2016)	Wild Bees and Honey Bees	Sweden	Field	Honey bee and wild bee competition across a grassland gradient	Interspecific competition between honey bees and bumble bees was reduced in areas with semi-natural grassland.
Koh et al. (2016)	Wild Bees	USA, national	GIS	Native bee habitat and pollination service models	Modeled native bee abundance declined by 23% from 2008 to 2013, mostly due to conversion of native habitat to row crops.
Kuchling et al. (2018)	Wild Bees and Honey Bees	Austria	Field and GIS	Landscape composition effects on colony mortality	Colonies in semi-natural areas, coniferous forests, and pastures had the lowest loss probability in four of six years.
Otto et al. (2016)	Honey Bees	Northern Great Plains, USA	GIS	Land-cover change around apiaries and landscape suitability modeling	Beekeepers favor grassland and Conservation Reserve Program lands when selecting apiary locations. These land covers are becoming less common in the Northern Great Plains.
Otto et al. (2018)	Honey Bees	Northern Great Plains, USA	GIS	Conservation Reserve Program effects on honey bees and landscape forecast modeling	Loss of Conservation Reserve Program from 2006-2016 decreased forage availability for honey bees. Future alterations to the national acreage cap of CRP will affect landscape suitability for supporting honey bees.
Park et al. (2015)	Wild Bees	New York, USA	Field	Pesticide effects on bees in relation to land use	Natural and semi-natural areas, including grasslands, provided a buffer against the effects of pesticides on wild bees.
Ricigliano et al.(2019)	Honey Bees	North Dakota, USA	Field	Conservation Reserve Program effects on honey bee health	Honey bee colonies located around Conservation Reserve Program fields showed improved performance and higher expression of vitellogenin, relative to colonies located near row crops.
Sanderson (2016)	Honey Bees	North Dakota, USA	Field	Quantify land covers adjacent to apiaries	Apiaries are most often adjacent to perennial grasslands, relative to other land covers.
Smart et al. (2016a)	Honey Bees	North Dakota, USA	Field	Honey bee colony survival and honey production in relation to land cover	Honey bee colonies surrounded by bee-friendly crops and grasslands had higher survival rates and produced more honey.
Smart et al. (2016a)	Honey Bees	North Dakota, USA	Field and Lab	Individual bee and colony health in relation to land use	Colonies and individual bees positioned in grasslands had improved individual bee health and colony survival.
Smart et al. (2017)	Honey Bees	North Dakota, USA	Field	Pollen forage diversity in relation to land cover	No difference in bee-collected pollen diversity was detected across grassland land-cover gradient.
Smart et al. (2018)	Honey Bees	Northern Great Plains, USA	Field	Honey bee colony growth and beekeeper revenue in relation to land cover	Honey bee colonies located in grasslands were larger relative to those surrounded by row crops. This difference affected pollination service payments and other revenue for beekeepers.
Sponsler and Johnson (2015)	Honey Bees	Ohio, USA	Field	Colony success in relation to landscape composition	Colony food accumulation and wax production were positively related to cropland and negatively related to grassland and forest.

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