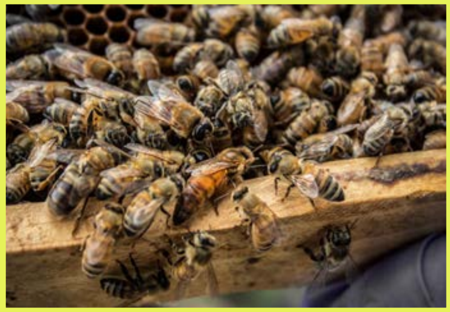


Why Does Bee Health Matter? The Science Surrounding Honey Bee Health Concerns and What We Can Do About It

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Introduction

Honey bees with access to better and more complete nutrition exhibit improved immune system function and behavioral defenses for fighting off effects of pathogens and pesticides.

A colony of honey bees is an amazing organism when it is healthy; it is a superorganism in many senses of the word. As with any organism, maintaining a state of health requires cohesiveness and interplay among cells and tissues and, in the case of a honey bee colony, the bees themselves. The individual bees that make up a honey bee colony deliver to the superorganism what it needs: pollen and nectar collected from flowering plants that contain nutrients necessary for growth and survival. Honey bees with access to better and more complete nutrition exhibit improved immune system function and behavioral defenses for fighting off effects of pathogens and pesticides (Evans and Spivak 2010; Mao, Schuler, and Berenbaum 2013; Wahl and Ulm 1983).

Sadly, as this story is often told in the headlines, the focus is rarely about what it means for a honey bee colony to be healthy and is instead primarily focused on colony survival rates. Bee colonies are chronically exposed to parasitic mites, viruses, diseases, miticides, pesticides, and poor nutrition, which weaken and make innate defenses insufficient at overcoming these combined stressors. Colonies that are chronically weakened can be

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Photo sources: Clint Otto (left); Sarah Scott (center/right)

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even more susceptible to infections and levels of pesticide exposure that might otherwise be innocuous, further promoting a downward spiral of health. Sick and weakened bees diminish the colony's resiliency, ultimately leading to a breakdown in the social structure, production, efficiency, immunity, and reproduction of the colony, and eventual or sudden colony death.

Since 2006, there has been a tragic breakdown in honey bee health.

Since 2006, there has been a tragic breakdown in honey bee health. Frequently referred to as colony collapse disorder, this erosion of honey bee health has taken place on an enormous scale, affecting most of North America and parts of Europe. Survey data indicate that the average winter mortality of colonies across the United States has ranged from 22 to 37%, and the average yearly mortality from 35 to 45% (Lee et al. 2015; Seitz et al. 2016). These losses are well above the historical 15 to 18% that beekeepers consider acceptable winter attrition. The persistent high colony mortality puts economic pressure and responsibility on beekeepers to replace their losses by purchasing more colonies from other beekeepers, or by dividing their surviving colonies. In part because of unprecedented demand for honey bees to pollinate crops, especially almonds in California, and through these practices, the number of bee colonies in the United States is actually increasing (USDA–NASS 2016a), despite significant replacement costs and declines in overall health.

Honey bees depend entirely on flowering plants for their nutrition. In turn, human nutrition depends heavily on honey bees for pollination of fruits and vegetables, adding value to consumers' diets and wallets.

The public should be concerned about honey bees because their pollination services contribute directly to the economy and food security. Honey bees depend entirely on flowering plants for their nutrition. In turn, human nutrition depends heavily on honey bees for pollination of fruits and vegetables, adding value to consumers' diets and wallets. The annual revenue from the sale of honey bee pollinated fruit, vegetable, and nut crops in the United States is estimated at $11.7 billion (Calderone 2012). The additional value of pollination services by the thousands of species of native bees that live in the wild throughout the United States is estimated at $3.4 billion annually (Calderone 2012), and the total economic value of pollination worldwide, by all bees, was estimated at €153 billion (US$216 billion) (Gallai et al. 2009). Fruits and vegetables (e.g., apples, almonds, blueberries, cucumbers, melons, and squashes) pollinated by all bees add flavor, texture, and color to consumers' diets, but more importantly, they are low-calorie, low-fat sources of fiber, vitamins, and minerals. As their name suggests, honey bees produce copious amounts of honey. For example, in 2015 commercial beekeepers in the United States removed approximately 156 million pounds (70,760,410 kilograms [kg]) of honey from their honey colonies, an agricultural product worth about $387 million (USDA–NASS 2016a).

Aside from the direct and indirect benefits derived from their pollination services, honey bees support diverse assemblages of plant communities that sustain wildlife and, intangibly, add to the quality of life.

Further, consumers reap the benefits of pollination services honey bees provide to crops grown for seed production. The value of seed produced from legume hays, carrots, and onions is estimated to be $5.4 billion (Calderone 2012). High-quality forage (e.g., alfalfa hay) grown from seed produced via honey bee pollination aids other sectors of agriculture such as livestock and dairy production. Aside from the direct and indirect benefits derived from their pollination services, honey bees support diverse assemblages of plant communities that sustain wildlife and, intangibly, add to the quality of life.

One striking example of the contribution that honey bees make to U.S. agriculture is their pollination of nearly 405,000 hectares (one million acres) of almond trees that grow in the Central Valley of California. This state produces approximately 82% of the world's almonds, yielding 907,200 tonnes (two billion pounds [lbs]) of nuts worth $5.3 billion in 2015 (Almond Board of California 2015; USDA–NASS 2016b). Pollination of the almond flower is almost entirely accomplished by honey bees. Growers typically rent two colonies per acre to ensure adequate pollination of their almonds—meaning approximately two million colonies are needed for almond pollination. With an estimated 2.66 million colonies in the United States (USDA–NASS 2016a), the sheer acreage of almond orchards necessitates that most of the nation's honey bees be transported to California in the winter to be available at the start of the almond bloom in February.

Many commercial beekeepers (those who earn their livelihood from beekeeping) derive the majority of their income from renting their colonies for pollination services rather than honey production.

The almond crop is a chief source of income for many growers—but also many beekeepers. In fact, many commercial beekeepers (those who earn their livelihood from beekeeping) derive the majority of their income from renting their colonies for pollination services rather than honey production. The transportation and presence of such a large number of colonies in one area is a unique situation not seen anywhere else in the world. Commercial beekeepers make a business decision whether or not to rent their colonies for almond pollination based on consideration of the benefits and risks. The majority of beekeepers have a good partnership with almond growers to ensure good crop production and the protection of their indispensable pollinators from pesticide exposure. The high density of colonies, however, increases the risk of disease and parasite transmission among colonies. Additionally, because there are insufficient floral resources in California to support such a high density of honey bee colonies year-round, beekeepers must transport their colonies back to other states, at considerable expense and risk of spreading diseases and parasites from the other apiaries across the nation, after the end of the brief almond bloom period.

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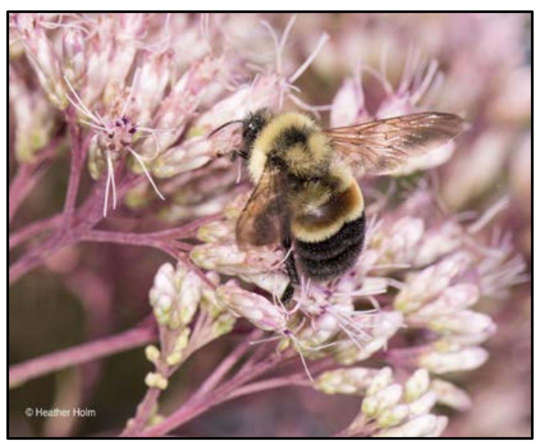
In the last 10 years, the public has taken a keen interest in the plight of honey bees. The outpouring of concern has led to increased direction of funding for research as well as a number of federal and state legislative initiatives to help increase and protect forage for honey bees and other pollinators. This includes the 2014 Presidential Memorandum on pollinator health, and subsequent Pollinator Partnership Action Plan, highlighting the need to restore and enhance pollinator habitat acreage through federal actions and public/private partnerships (Executive Office of the President 2014). Through this action plan, federal agencies such as the U.S. Department of Agriculture, U.S. Environmental Protection Agency, and Department of Interior are collaborating with other federal and state agencies, universities, and nongovernmental organizations to monitor colony health, identify solutions, and mitigate bee decline. In addition, most states have or are developing their own state Managed Pollinator Protection Plan or MP3 to enhance communication and collaborations among growers, beekeepers, pesticide applicators, and policy-decision makers with the goal of mitigating pollinator decline while maintaining economic growth. Backyard beekeeping has also become increasingly popular in urban areas across the nation during this time, and local beekeeping and advocacy groups have started new initiatives to help honey bees.



This bumble bee (*Bombus affinis*), which is native to the United States, was recently placed on the endangered species list.

Some of our native bees, such as certain species of bumble bee, are in more severe decline than our managed honey bees, emphasizing the need for more research on native pollinators.

Concomitantly, there has been a long-overdue interest in the thousands of species of native bees and other insect pollinators that contribute invaluable, and mostly unquantified, service toward the pollination of fruits, vegetables, and other flowering plants. In fact, some of our native bees, such as certain species of bumble bee, are in more severe decline than our managed honey bees, emphasizing the need for more research on native pollinators (Burkle, Marli, and Knight 2013; Colla et al. 2012; Committee on the Status of Pollinators in North America 2007; Koh et al. 2016).

Research is rapidly documenting the many stresses all bees are facing. Most scientists agree that there are four main stressors: parasites, pathogens, pesticides, and poor nutrition. These stressors interact to produce unwanted outcomes that compromise honey bee health. The same stressors also affect native bee communities. For honey bees, research could generate novel ways to combat the most devastating parasites and pathogens (e.g., *Varroa* mites and viruses). But controlling only these two stressors would not solve the problem for honey bees and other pollinators. Good nutrition, which for bees comes from the landscape, is the foundation of a healthy, productive colony. Land-use change, particularly in agricultural regions, has decreased the availability of abundant and diverse forage habitat on the landscape. Remaining habitat for honey bee and native bee forage and nesting has become increasingly disrupted, fragmented, and contaminated by agrochemicals as frequent detections of pesticide residues are found in bee-collected pollen and nectar (Long and Krupke 2016; Mullin et al. 2010; Sanchez-Bayo and Goka 2014).

Research is rapidly documenting the many stresses all bees are facing. Most scientists agree that there are four main stressors: parasites, pathogens, pesticides, and poor nutrition.

Exposure to pesticides in many areas is common, yet mechanisms for reporting colony losses and identifying the source of contamination are deficient and variable based on state and local government agencies. Although people on farms and in cities are ready and willing to take action to protect bees and other beneficial insects, their actions are impeded by a lack of financial incentives, lack of abundant seeds to plant pollinator habitat on large scales, and lack of education about ways to protect pollinators while applying pesticides. Removing these obstacles by (1) developing better usage and incident reporting data systems; (2) generating more and better training for pesticide applicators; (3) increasing awareness about the importance of integrated pest management (IPM), both for pesticide applicators and beekeepers; and (4) modifying landscape practices to accommodate honey bees, native bees, and other beneficial insects would generate real and positive change.

Direct Threats to Colony Health: *Varroa destructor* and Viruses

Varroa destructor, a parasitic mite that originated in Asia, was inadvertently spread throughout much of the world via transportation of bee colonies. It arrived in the United States in 1987. *Varroa* lives and reproduces only within a honey bee colony where it feeds exclusively on bee tissue, specifically the fat body (Ramsey, S. and D. vanEngelsdorp. Personal communication). To reproduce, a mite lays eggs on a bee pupa developing within a wax-capped cell. The mite offspring mate within the cell, and the adult female mites emerge from the cell along with the adult bee. Mites move from bee to bee and eventually enter another cell containing developing brood to continue the life cycle. The mites' feeding weakens the adult bee, decreases the bee's adult lifespan, and compromises the bee's immune system (Dainat et al. 2012; Yang and Cox-Foster 2005).

Varroa destructor, a parasitic mite that originated in Asia, was inadvertently spread throughout much of the world via transportation of bee colonies.

High levels of *Varroa* mites in a colony can impair physiological features in infected bees, which decreases worker longevity and eventually leads to colony death. These negative impacts on bees from *Varroa* mite feeding include reduced body weight, abdominal carbohydrates, and key proteins needed for overwintering (Amdam et al. 2004). The main damage to the colony is usually not due to the mite, however, but to the bee viruses the mite vectors. Mites acquire and transfer bee viruses as they feed on and move from bee to bee. Several viruses are prevalent and may persist in honey bee colonies without causing symptoms; however, suppression of honey bee immunity caused by mites as they feed permits viral replication, resulting in elevation in viral load likely promoting bee morbidity and death. Unlike human and mammalian immune systems, the honey bee immune system has no antibodies, so there is no effective way to vaccinate bees against viruses. Instead, most beekeepers depend on managing the level of *Varroa* mites in their colonies to help lessen risk of virus transmission.

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Bees are often exposed to mites, viruses, and other diseases in areas of high colony density, whether in urban or agricultural scenarios. This spread of diseases and parasites among colonies is what epidemiologists refer to as "horizontal transmission." Research is very clear that with sustained horizontal transmission, the virulence of pathogens and parasites increases (Bull 1994; Lipsitch and Moxon 1997), which appears to be happening with the *Varroa*-virus complex (e.g., deformed wing virus). In contrast, where densities of bee colonies are low, horizontal transmission among colonies is decreased, leading to relatively healthier colonies that require fewer, if any, treatments to control mites and diseases.

The sustained use of miticides to control *Varroa* has led to problems.

Solutions to the *Varroa*-virus Disease Complex

Since the introduction of *Varroa* into the United States, most beekeepers have managed the level of *Varroa* mites in their colonies by treating with miticides composed of synthetic or organic ingredients. The sustained use of miticides to control *Varroa* has led to problems: the mites have evolved resistance to some of the chemicals, and the wax combs—the nest in which the superorganism lives, stores food, and rears its young—have become contaminated with miticide residues (Mullin et al. 2010). Because of these ongoing problems, it is important to develop novel IPM approaches to decrease the threat of *Varroa* and viruses that do not involve the use synthetic miticides—preferably through strategies that rely on bees' natural defenses, or through the use of molecular or mechanical techniques.

There are pockets of beekeepers using locally adapted stocks in the United States and Europe who are having success at keeping their honey bees without treating for mites.

Some beekeepers are employing nonchemical strategies to manage *Varroa*. There are pockets of beekeepers using locally adapted stocks in the United States and Europe who are having success at keeping their honey bees without treating for mites. The locally adapted stocks evolved because beekeepers allowed many colonies to die so that natural selection could take its course. In most cases, the beekeepers employing this strategy are small scale and located in relatively remote areas where surrounding colony density, and thus horizontal transmission of mites, is relatively low (Seeley and Smith 2015). Beekeepers that try to employ natural selection for locally adapted stocks in areas of high colony density have less success because of the high level of horizontal transmission of mites among neighboring beekeepers, which makes it difficult to keep mite levels low enough for continued colony survival. Commercial beekeepers and growers of fruit, vegetable, and almond crops cannot afford to allow colonies to die so that natural selection can take its course on the few surviving colonies. Beekeepers' income and food security depends on keeping sufficient numbers of colonies alive to satisfy pollination contracts. Instead, large-scale beekeepers could regain some vitality and productivity from investment in new, and enhancement of existing, bee breeding programs that could decrease the frequency of miticide treatments (e.g., Rinderer et al. 2014).

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Honey bees can be bred for behaviors that decrease mite levels.

Honey bees can be bred for behaviors that decrease mite levels—such as hygienic behavior and "*Varroa*-sensitive hygiene," in which bees detect and remove mite-infested brood from the nest (e.g., Boecking and Spivak 1999; Harbo and Harris 2005; Harbo and Hoopingarner 1997; Spivak 1996; Wilson-Rich et al. 2009), or grooming behavior, in which bees remove mites that are riding on adult bees and physically damage the mites (reviewed in Pritchard 2016). Increased federal funding would strengthen bee breeding research and provide hands-on assistance and training to beekeepers to help them effectively implement these breeding programs for mite resistance.

In addition, it is important to develop new ways to control mites.

In addition, it is important to develop new ways to control mites. Emerging technologies in genetic engineering have been shown to effectively modify and alter the expression of host genes (e.g., RNAi [ribonucleic acid interference] and CRISPR/Cas9 [clustered regularly interspaced short palindromic repeats/CRISPR-associated]), which could, in the future, improve bee resiliency or diminish parasite and pathogen virulence. Ribonucleic acid interference is thought to have evolved as a means of protecting the host organism from invasion by foreign genetic material, such as viruses. Field trials are currently ongoing in which RNAi is being used to target biochemical processes vital to the survival of the *Varroa* mite. These technologies are currently in research and development; however, as with any new technology, thorough consideration of their effectiveness and safety must be verified before they are deployed on a large scale.

There is no one-size-fits-all solution to the *Varroa*-virus problem for all beekeepers.

There is no one-size-fits-all solution to the *Varroa*-virus problem for all beekeepers. To effectively manage *Varroa*, beekeepers need regionally adapted, operation-specific, and context-dependent best management practices (BMPs). Educating and encouraging beekeepers to establish regional bee breeding programs for locally adapted and genetically diverse stocks that survive better in relatively remote areas under local climatic conditions is a highly desirable goal. New educational efforts are needed, however, to assist backyard beekeepers in cities or other areas where locally adapted stocks are not available and where colony density and horizontal transmission of mites and viruses is very high. University extension programs can assist commercial bee breeders in selecting stocks that are more resistant to *Varroa*. Targeted research efforts are needed to provide new, less risk-prone ways to control *Varroa*, particularly for commercial beekeepers who transport bees for pollination of our nation's food supply.

New programs are helping beekeepers become more informed about the level of mites and diseases that cause damage to their colonies so they can make timely and effective management decisions.

Additional funding for extension and education would improve communication and implementation of best practices for beekeepers who work at the scale of their business. New programs are helping beekeepers become more informed about the level of mites and diseases that cause damage to their colonies so they can make timely and effective management decisions. For example, the Mite Check program, offered through the Bee Informed Partnership, encourages backyard beekeepers to sample and report mite levels on a regional basis. The Bee Tech-Transfer Teams, also operating through the Bee Informed Partnership, assist commercial beekeepers in monitoring mite and disease levels. Increased federal support for these boots-on-the-ground extension and education programs that provide beekeeper training would help to improve management of mites and diseases at the regional level, and better communicate effective solutions. Furthermore, additional research and technologies are needed for developing novel approaches to combating current and future bee pathogens.

Other Diseases and Antibiotics

Before 1987, the list of diseases affecting honey bees was relatively short.

Before 1987, the list of diseases affecting honey bees was relatively short. Developing larvae were at risk of contracting two bacterial diseases: American foulbrood (*Paenibacillus larvae*), a lethal disease; and European foulbrood (*Melissococcus plutonius*), a more moderate and seasonal disease. In addition, a seasonal and moderate fungal disease, chalkbrood (*Ascosphaera apis*), infected bee larvae. Adult bees could become infected with a fungal-like microsporidian pathogen (*Nosema apis*) or parasitized with the tracheal mite (*Acarapis woodi*). With the exception of chalkbrood, beekeepers managed the diseases mainly by incinerating the bee colony and contaminated equipment (in the case of American foulbrood) or in-colony application of antibiotics or other chemotherapeutics, both prophylactically and as a treatment. Viruses were typically found in adult bees at low levels and were mostly asymptomatic. There are still occasional outbreaks of American foulbrood, European foulbrood, and chalkbrood, but they have a minor role in recent colony losses (vanEngelsdorp and Meixner 2010).

In 2006, surveillance efforts were key in reporting widespread distribution of a previously unrecognized microsporidian pathogen, *Nosema ceranae*, in colonies throughout the United States and other parts of the world (Cox-Foster et al. 2007). Treatment with the antibiotic fumagillin has long been used prophylactically for the control of the previously common relative, *Nosema apis*. Scientists are now learning that the use of fumagillin can pose risks to colony health because improper doses may lead to

The use of antibiotics in bee colonies in the United States will be regulated for the first time beginning in 2017.

proliferation, rather than reduction, of *Nosema* spores in the gut of bees (Huang et al. 2013). For most beekeepers, the use of this antibiotic to treat *Nosema* is not worth the expense and risk. In fact, the use of antibiotics in bee colonies in the United States will be regulated for the first time beginning in 2017. Beekeepers will need to have a prescription from a veterinarian to obtain antibiotics to treat their honey bee colonies for American and European foulbrood diseases. This new regulation follows the current trends in livestock management and human health that are focusing on curtailing chronic and preventative uses of antibiotics. The regulation and decrease of antibiotic use in bee colonies is laudable and will help improve the sustainability of beekeeping.

Pesticides

Despite their enormous benefit in controlling unwanted pests, pesticides can have nontarget effects if they are applied or persist in a way that poses direct or indirect risks to beneficial organisms such as bees.

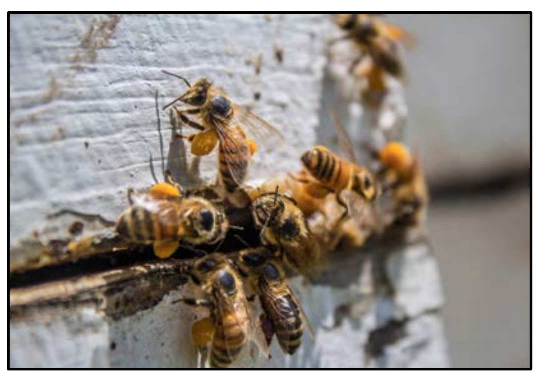
Pesticides include insecticides, herbicides, fungicides, insect growth regulators (IGRs), and other chemicals that broadly target particular groups of organisms. Despite their enormous benefit in controlling unwanted pests, pesticides can have nontarget effects if they are applied or persist in a way that poses direct or indirect risks to beneficial organisms such as bees. Applications of insecticides (e.g., organophosphates, pyrethroids, and IGRs) are sometimes sprayed directly on blooming flowers or drift onto nearby flowers where bees are foraging, potentially exposing the bees and many other beneficial insects to lethal or sublethal doses. Allowing an insecticide, with demonstrated toxicity to bees, to drift is a violation of the federal label. This type of violation, however, is difficult to enforce in most states, and colonies harmed by potential drift are often not directly observed and/or reported by beekeepers.

In an attempt to decrease human exposure risks and nontarget effects due to spray drift, a new class of insecticides, the neonicotinoids, was developed in the 1990s.

In an attempt to decrease human exposure risks and nontarget effects due to spray drift, a new class of insecticides, the neonicotinoids, was developed in the 1990s. Neonicotinoids are systemic, meaning they move through the vascular system of the plant, and can be applied directly to the seed as seed coating, sprayed onto the foliage, or applied to the soil surrounding the plant. Neonicotinoids are an attractive option because they have low acute toxicity to humans and mammals but very high acute toxicity to insects—ten thousand times more toxic to insects than mammals (Pisa et al. 2015). Systemic insecticides may persist in plant tissues or soil for long periods of time, in some cases more than a year (USEPA–EFGWB 1993), which violates the basic tenet of IPM and BMPs regarding treating only when needed. For bees, the problem is that a systemic insecticide can move into the pollen and nectar produced by the plant where bees may be exposed when foraging on flowers.

Dust from seed coatings embedded with neonicotinoids can unintentionally be released by farm equipment during planting and drift onto neighboring plants contaminating nectar, pollen, and water sources for foraging bees.

Although many studies show neonicotinoid seed-treated crops yield low residue levels in nectar and pollen, dust from seed coatings embedded with neonicotinoids can unintentionally be released by farm equipment during planting and drift onto neighboring plants contaminating nectar, pollen, and water sources for foraging bees (Bonmatin et al. 2005; Botías et al. 2015; Cutler and Scott-Dupree 2007; Krupke et al. 2012; Schmuck et al. 2001). Exposure to neonicotinoids through contaminated pollen and nectar may lead to subtle behavioral and developmental impairments (e.g., foraging, flight orientation, learning and memory, egg laying, grooming, brood production) and complicated health symptoms in



Honey bees returning to the hive with yellow pollen loads on their hind legs. (Photo courtesy of Sarah Scott.)

bees, particularly when the effects interact with *Varroa*, diseases, and nutritional deficiencies (Di Prisco et al. 2013; Dively et al. 2015; Pettis et al. 2013).

Good communication among beekeepers, growers, and pesticide applicators would help everyone understand their shared responsibility to protect bees and the ecosystem services they provide.

Currently, there is a national discussion focused on instituting MP3s and how they may encourage practices that decrease chronic pesticide exposure to pollinators. Increased communication between pesticide applicators and beekeepers is stressed in most MP3s so that a beekeeper can be notified of an impending pesticide application. Increased communication between parties that may have competing interests is a positive step forward. Notification by an applicator, however, puts the burden on the beekeeper to protect his or her colonies rather than on the applicator to make changes to avoid exposure to bees. A beekeeper cannot realistically protect colonies at risk by covering or closing colonies to restrict flight of the bees. Moreover, moving colonies to different locations puts the bees at risk of exposure by a different applicator that does not know the colonies were moved, and it costs the beekeeper significant time, labor, and money. Good communication among beekeepers, growers, and pesticide applicators would help everyone understand their shared responsibility to protect bees and the ecosystem services they provide.

Solutions to the Pesticide Part of the Problem

There are concrete ways that bees and beneficial insects could be protected from unwanted and unintentional pesticide exposure. The following are BMP suggestions that would lead to substantial decreases in exposure and increased safety of pollinators around pesticide applications. To be effectively adopted at a national scale, these BMPs need to be better communicated to a diverse group of agricultural producers, pesticide applicators, landowners, beekeepers, educators, and policy advisers. Federal investment could be used to strengthen existing university extension and outreach programs to communicate BMPs to multiple stakeholders and develop implementation strategies for agricultural producers and commercial beekeepers. Similar to combating bee pathogens, investment in applied scientific research will help mitigate the impacts of pesticides on bee health and contribute to sustainable agriculture and environmental health.

One best management practice is to curtail the off-target drift of all pesticides.

One BMP is to curtail the off-target drift of all pesticides. Decreasing drift would increase efficacy of the pesticide and decrease cost of application for farmers, and it would protect pollinators from unintended exposure. Research and development is under way to modify the seeding equipment and seed coatings so that, at the time of crop planting, highly acute levels of insecticide dust (i.e., neonicotinoids) from pesticide-coated seeds do not drift onto flowering plants in the vicinity of the target field(s). Other research is needed to develop new mechanical and chemical engineering methods to decrease drift of other pesticides off the target crop. Flowering plants outside crops targeted with herbicide (e.g., glyphosate-resistant crops) are critical for bee nutrition and health because they provide pollen and nectar resources for bees. Decreasing the drift of herbicides outside target fields during the rest of the growing season maintains the availability of these flowering resources for pollinators. Properly calibrating equipment and being cognizant of optimal weather conditions can minimize pesticide drift from spray applications. Weatherwise applications avoid high-temperature and low-humidity conditions and windy days. Air inversion (occurs when soil surface air is cooler then air above) and air turbulence (occurs when soil surface air is warmer then air above) may also increase the risk of nontarget drift.

Pollinator-friendly integrated pest management strategies are being developed by many universities and extension agencies to further safeguard pollinators in agricultural and urban settings.

The use of IPM approaches in both grower and beekeeper operations is another BMP that will improve the timing and effectiveness of chemicals and decrease pesticide exposure on bees. Pollinator-friendly IPM strategies are being developed by many universities and extension agencies to further safeguard pollinators in agricultural and urban settings. More details on available pollinators and pesticide stewardship guides can be obtained through local extension agencies, universities, and or state MP3s.

A third BMP is to follow and enforce the pesticide label. The label is the law. To improve proper pesticide use and disposal, pesticide users and applicators need to be provided clear guidance on understanding pesticide labels, which indicate potential toxicity to bees, restrictions on application when bees are foraging (i.e., during daylight hours), and avoiding application when wind leads to drift onto nearby flowers. Improvements could be made to pesticide labels and regulations to further decrease pesticide exposure on bees.

Toxicity testing and risk assessments on all new pesticides, including fungicides, should be expanded beyond the designated surrogate species, the honey bee (*Apis mellifera*), and performed on other *Apis* and non-*Apis* bees and their larvae before being approved for widespread use.

Pesticide formulations vary in toxicity to bees depending on the additive or adjuvant ingredients included in the formulation or added to the spray tank to enhance activity or application characteristics. For example, organosilicone surfactants have been shown to harm bees alone, but pesticide labels do not indicate potential toxicity of additive ingredients (Mullin et al. 2016). Listing all ingredients on the label, not just the active ingredients in a pesticide formulation, and providing residual persistence and toxicity information on the labels for all harmful compounds and common spray tank adjuvants would allow consumers to make informed decisions such as avoiding pesticide formulations with harmful adjuvants—e.g., organosilicones. Toxicity testing and risk assessments on all new pesticides, including fungicides, should be expanded beyond the designated surrogate species, the honey bee (*Apis mellifera*), and performed on other *Apis* and non-*Apis* bees and their larvae before being approved for widespread use. Mixtures of pesticides (especially those commonly used in tank mixes) should be tested for synergistic toxicity to bees, particularly if they contain ergosterol biosynthesis-inhibiting fungicides (Iwasa et al. 2004; Pilling and Jepson 1993), which can synergize with insecticides in the mix to increase toxicity.

Motivated by fear of being asked to vacate a farmer's property, many beekeepers will not report losses despite incurring significant financial harm and colony loss.

Establishment and maintenance of publicly available, commercial pesticide-use records and apiary locations would allow beekeepers, researchers, and regulators to investigate bee incidents from pesticide exposure or eliminate pesticides as a potential cause. This level of transparency follows the lead of California and New York. Unsequestered and anonymous incident reporting mechanisms are equally essential in developing effective measures to decrease pesticide losses. Currently many regulatory authorities do not share incident reports with other jurisdictions, including the U.S. Environmental Protection Agency, and in many cases, the regulatory authority will not perform an investigation unless a claim is filed. Motivated by fear of being asked to vacate a farmer's property, many beekeepers will not report losses despite incurring significant financial harm and colony loss.

In addition to improvements in commercial pesticide application and monitoring, better education and clear language regarding usage on "over-the-counter" pesticides available for purchase and use by homeowners would greatly benefit pollinator communities in urban settings (Church et al. 2012). This may include the elimination or decrease of systemic insecticide use on flowering ornamental trees and nursery plants from which bees collect pollen and nectar. Finally, more educational efforts and awareness to homeowners about the overuse and dependency of cosmetic pesticides, or pesticides used for aesthetic purposes, and to growers about the effectiveness of IPM approaches will greatly improve and address the impacts of pesticides on pollinators in a sustainable way.

Honey bees forage up to 8.4 km (5 miles) from their colony in search of food; the average foraging trip is approximately 3.2 km (2 miles).

Floral Nutrition, Land Use, and Beekeeping

All bees require a nutritional balance of protein, amino acids, carbohydrates, vitamins, and minerals, which they obtain from the pollen and nectar of flowering plants. Honey bees forage up to 8.4 kilometers (km) (5 miles) from their colony in search of food; the average foraging trip is approximately 3.2 km (2 miles). A two-mile radius around a bee colony encompasses an area of 3,240 hectares (8,000 acres). Honey bees must visit approximately two million individual blossoms in order to produce a single pound (0.4 kg) of honey. A healthy honey bee colony can consume as much as 90.72 kgs

(200 lbs) of honey in a year before a single pound (0.4 kg) can be considered surplus available for harvest by the beekeeper. In addition to nectar, and perhaps more importantly, an abundance of diverse pollen (up to 18.1 kg [40 lbs] per colony per year) is crucial to the development of immature honey bees and population growth.

Research is clear that quality floral nutrition moderates the impact of pathogens and parasites of bees, and it decreases the sensitivity of bees to the effects of pesticides.

Research is clear that quality floral nutrition, in the form of pollen and nectar, moderates the impact of pathogens and parasites of bees, and it decreases the sensitivity of bees to the effects of pesticides (Alaux et al. 2011; Huang 2012; Mao, Schuler, and Berenbaum 2013; Wahl and Ulm 1983). In times of natural flower dearth, colonies must be fed supplemental protein (patties) and carbohydrates (usually liquid sugars) to maintain food supplies and brood rearing. These artificial feeds do not provide the same health benefits as abundant and diverse flowers, and they are not a solution to the problem of a lack of flowers.

Case in Point: Beekeeping in the Northern Great Plains

The business model of commercial beekeepers mirrors other modern agriculture business models, which is to maximize production in order to meet demand and overcome increasing costs. Unfortunately, these same trends in modern agriculture have adversely affected commercial beekeeping. In the past decade, high commodity prices, biofuel mandates, federal crop insurance, conservation policy changes, and agriculture innovation have helped drive expansion in row crop (mainly corn and soybeans) farming in the Northern Great Plains (NGP) region of the country, where traditionally many commercial colonies spend a significant and critical part of the year (Otto et al. 2016; Wright and Wimberly 2013).

Apiary containing 36 honey bee colonies (4 colonies per pallet) in North Dakota. (Photo courtesy of Ben Carlson.)

Although honey bee colonies are distributed among all U.S. states, the greatest amount of honey production and highest colony numbers are concentrated in a relatively few number of states during the summer months.

Although honey bee colonies are distributed among all U.S. states, the greatest amount of honey production and highest colony numbers are concentrated in a relatively few number of states during the summer months (Table 1), with four of the top seven states (>40% overall) occurring in the NGP. For multiple generations, the NGP has functioned as an unofficial bee refuge, offering many beekeepers a stable base of operations and honey bee colonies a welcome respite to recover from the stresses imposed on them from the migratory realities of the U.S. pollination service circuit. In general, beekeepers in this region try to place their colonies in close proximity to forage areas such as grasslands, pastures, tree rows, wetlands with vegetated buffers, and some agricultural crops such as alfalfa, canola, or sunflowers (Gallant, Euliss, and Browning 2014). Beekeepers in the NGP tend to avoid placing their colonies in close proximity to large-scale commodity crops such as corn and soybeans, and to a lesser extent small grains (Otto et al. 2016), because these areas provide little forage for bees and may increase exposure to pesticides.

Although much of the expansion of corn and soybean acres in the NGP has come at the expense of small grain and other row crop acreage, there has also been a substantial concurrent decline in various grasslands such as haylands, rangelands, and U.S. Department of Agriculture (USDA) Conservation Reserve Program (CRP) lands over the same period of time (Otto et al. 2016). For example, between 2006 and 2016 there was a loss of 729,000 hectares (1.8 million acres) of land enrolled in CRP in North Dakota

Conversion of grassland to cropland eliminates flowering plants that honey bees, and native bees, depend on for forage.

alone (USDA 2016). Since 2007, more than 294,000 hectares (726,180 acres) of CRP was converted to corn and soybean cultivation in the NGP and Upper Midwest (Morefield et al. 2016). Conversion of grassland to cropland eliminates flowering plants that honey bees, and native bees, depend on for forage. Often, lands that are converted to agriculture are planted as monocultures, providing little or no forage value for bees throughout the growing season. Crops planted on these newly converted agricultural fields are often preemptively treated with insecticides and fungicides to control undesirable pests. Additionally, most commercially grown corn and soybean varieties are genetically modified to be herbicide tolerant. As a result, weed suppression and mowing in noncropped areas may lead to a decreased ability of croplands to support abundant flowering habitat. Thus, land-use conversion decreases foraging opportunities for pollinators and may increase the pesticide exposure risk.

Land-use conversion decreases foraging opportunities for pollinators and may increase the pesticide exposure risk.

Table 1. Top 10 U.S. states supporting honey bee colonies and associated honey production, 2015 (Source: USDA–NASS 2016c)

State	Colonies	Lbs/Kgs per Colony	Total Honey (lbs/kgs x 1,000)
*North Dakota	490,000	74/33.57	36,260/16,447
*South Dakota	290,000	66/29.94	19,140/8,682
California	275,000	30/13.61	8,250/3,742
Florida	220,000	54/24.49	11,880/5,389
*Montana	146,000	83/37.65	12,118/5,497
Texas	126,000	66/29.94	8,316/3,772
*Minnesota	122,000	68/30.84	8,296/3,763
Michigan	90,000	58/26.31	5,220/2,368
Idaho	89,000	32/14.51	2,848/1,292
Washington	73,000	44/19.96	3,212/1,457
Proportion of United States	0.72	-	0.74

*Indicates states considered part of the Northern Great Plains

Other types of land management may also impact honey bee forage in the Northern Great Plains—for example, the use of broadcast spraying of herbicides and intensive mowing regimes on roadsides, ditches, field margins, and rights-of-way.

Whereas corn and soybean crop acres or yields are the largest in history, U.S. honey production has declined over the last decade. In the United States, the average yield per colony in 2000 was 38.1 kg (84.1 lbs); in 2014 it was 29.5 kg (65.1 lbs), a 23% reduction. Colonies positioned in apiaries surrounded by such intensively managed agricultural land have been shown to fare worse in health, honey production, and annual survival when compared to colonies surrounded by more uncultivated lands (Smart et al. 2016a,b).

Other types of land management may also impact honey bee forage in the NGP—for example, the use of broadcast spraying of herbicides and intensive mowing regimes on roadsides, ditches, field margins, and rights-of-way. Such patterns of land management are particularly concerning because these seemingly small areas may represent a significant portion of the total forage base for bees in agricultural landscapes. Often these areas harbor a diverse array of desirable native plants and valuable introduced species that are killed along with targeted invasive weeds (Requier et al. 2015). Thus, land managers are faced with the delicate task of suppressing undesirable, invasive plants, while recognizing these plants may provide an important and limited resource for bees in agroecosystems (Bretagnolle and Gaba 2015).

Most beekeepers do not own the lands where they place their colonies and have little control over where their bees forage. Beekeepers must obtain permission prior to placing colonies on private lands. More than 60% of land in the United States is privately owned, and in the NGP private lands constitute approximately 80% of the total land area. As farming practices have changed, ideal bee landscapes have become more difficult to find. Too often, colonies are now located on sites with limited nutritional resources, which can quickly lead to other bee health issues. As honey bees in agricultural areas compete for scant floral resources and congregate with honey bees from neighboring apiaries, the potential for pest and disease transfer (horizontal transmission), and competition between beekeepers, is dramatically increased. This unfortunate downward spiral in bee health continues to play out in commercial apiaries around the country every year because agricultural expansion and pest management practices decrease the carrying capacity of the landscape for honey bees while also creating the potential for unserviceable demands for crop pollination.

Most beekeepers do not own the lands where they place their colonies and have little control over where their bees forage.

Commercial beekeepers are adapting to this changing agricultural world, but current trends in declining honey production, higher input costs, and higher colony mortality rates indicate that more help is needed if the beekeeping industry is going to overcome these challenges (Daberkow et al. 2009; vanEngelsdorp and Meixner 2010).

As honey bees in agricultural areas compete for scant floral resources and congregate with honey bees from neighboring apiaries, the potential for pest and disease transfer (horizontal transmission), and competition between beekeepers, is dramatically increased.

Solutions to Optimize Land Use to Improve Bee Health

The large proportion of privately owned lands in the United States highlights the role that landowner decisions play in the creation or elimination of habitat for honey bees, especially in rural parts of the country. Land-use decisions made by landowners in agricultural areas are primarily influenced by commodity crop markets, government subsidies, and U.S. Farm Bill policies (Claassen et al. 2011). Improving forage availability for pollinators is often of secondary consideration, or not considered at all. It cannot be emphasized enough that policy decisions and resulting law, such as agricultural subsidies, dictate agricultural land-use decisions, which in turn impact many aspects of the health of bee colonies, and their forage base, in agricultural landscapes. Thus, long-term solutions for improving forage for pollinators can be strengthened through the involvement of private landowners and agricultural producers.

The recent presidential memorandum (Executive Office of the President 2014) and subsequent *National Strategy to Promote the Health of Honey Bees and Other Pollinators* established several key goals for improving pollinator health and habitat throughout the United States (Pollinator Health Task Force 2015). The strategy calls for coordinated efforts across government agencies to address issues surrounding pollinator decline, specifically the impacts of forage availability on honey bee nutrition. Furthermore, the USDA has recently launched multiple conservation efforts designed to enhance habitat for pollinators in the Upper Midwest and NGP. The resulting efforts are part of the USDA–Farm Service Agency's CRP and the USDA–Natural Resources Conservation Service's Environmental Quality Incentives Program (EQIP), which are voluntary programs that provide financial and technical assistance to landowners who wish to implement conservation practices on their agricultural lands. Both the CRP and EQIP currently provide cost-sharing options for landowners who wish to plant conservation covers designed for honey bees and native bees. In addition to improving bee forage, USDA conservation land provides added benefits to a variety of ecosystem services such as wildlife habitat, carbon storage, prevention of soil erosion, and improved water quality (Euliss et al. 2011; Werling et al. 2014). In addition, higher cost-share rates or increased payments for land conservation programs would make these programs more enticing to private landowners, thereby improving the impact of these programs on bee habitat and other ecosystem services.

Long-term solutions for improving forage for pollinators can be strengthened through the involvement of private landowners and agricultural producers.

There are monetary and/or acreage caps on CRP and EQIP, however, that limit the scope and impact of such programs. Acreage cap increases, seeding specifications, targeting of locations likely to most benefit from the presence of pollinator forage, and prioritization of enrollees interested in specific pollinator-targeted seed mixes within USDA programs could be reevaluated to improve the impact and efficiency of such programs. Further, public-private partnerships such as the Honey Bee Health Coalition and nonprofit organizations such as the Xerces Society, the Pollinator Partnership, and a new collaboration between Project Apis m. and Pheasants Forever, called the Bee and Butterfly Habitat Fund, have made the establishment of forage habitat a priority while at the same time addressing and maintaining agricultural land productivity.

It is imperative to provide clean sources of high-quality floral nutrition for bees in urban and agricultural landscapes.

It is imperative to provide clean sources of high-quality floral nutrition for bees in urban and agricultural landscapes. One way to increase high-quality floral resources is to provide financial incentives for planting pollinator habitat on marginal land. Incentives could be negotiated through federal legislation such as the U.S. Farm Bill. In addition, pollinator plantings could be established along roadside ditches, buffer strips, utility corridors, and waterways, as well as within cities. Establishing pollinator planting in these areas would involve various federal and state agencies, water districts, and local government.

There is an urgency to create affordable seed mixtures and conservation practices that benefit honey bees as well as native bees.

As with any new initiative, proper planning will help to ensure that all stakeholders work toward a shared goal of improving pollinator forage. There is an urgency to create affordable seed mixtures and conservation practices that benefit honey bees as well as native bees. Using native plant species in pollinator conservation is important to support native bees and the environment in general; however, when specifically targeting honey bees, seed mixes containing introduced, noninvasive floral species that are widely used by honey bees may be considered, especially in agricultural areas. There is currently a broad consensus around the need to increase forage to support honey bee colonies and other pollinator species across the country. Furthermore, scientists have developed models to assist land managers with deciding where such forage may be situated to incur positive impact (Otto et al. 2016; Smart et al. 2016a). Land management activities and policy decisions that are informed through science will act to secure healthy populations of honey bees and wild pollinators over the long term, as well as a healthy and diverse agricultural food production system.

Finding solutions means realizing that there is a problem.

Finding solutions means realizing that there is a problem. Most scientists and beekeepers agree that honey bee health decline is the result of multiple stressors. Although some are simple enough, most of the stressors are interacting in nature. Honey bees positioned in landscapes dominated by row crops will benefit from increases in pollinator forage plantings. Bringing critical foraging opportunities and habitat back to such areas through careful and appropriate pesticide use, conservation, and sustainable agriculture practices will help ensure the availability of pollinators needed to secure a stable food supply.

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