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Forum

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Management of Arthropod Pathogen Vectors in North America: Minimizing Adverse Effects on Pollinators

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Abstract

Tick and mosquito management is important to public health protection. At the same time, growing concerns about declines of pollinator species raise the question of whether vector control practices might affect pollinator populations. We report the results of a task force of the North American Pollinator Protection Campaign (NAPPC) that examined potential effects of vector management practices on pollinators, and how these programs could be adjusted to minimize negative effects on pollinating species. The main types of vector control practices that might affect pollinators are landscape manipulation, biocontrol, and pesticide applications. Some current practices already minimize effects of vector control on pollinators (e.g., short-lived pesticides and application-targeting technologies). Nontarget effects can be further diminished by taking pollinator protection into account in the planning stages of vector management programs. Effects of vector control on pollinator species often depend on specific local conditions (e.g., proximity of locations with abundant vectors to concentrations of floral resources), so planning is most effective when it includes collaborations of local vector management professionals with local experts on pollinators. Interventions can then be designed to avoid pollinators (e.g., targeting applications to avoid blooming times and pollinator nesting habitats), while still optimizing public health protection. Research on efficient targeting of interventions, and on effects on pollinators of emerging technologies, will help mitigate potential deleterious effects on pollinators in future management programs. In particular, models that can predict effects of integrated pest management on vector-borne pathogen transmission, along with effects on pollinator populations, would be useful for collaborative decision-making.

Key words: vector-borne pathogen, conservation, IPM, Culicidae, Ixodidae

Vector-borne diseases cause serious public health problems worldwide, with tick-borne disease being of particular importance in North Temperate regions (Ginsberg and Faulde 2008). Lyme disease is the major vector-borne disease in North America and Europe, with ~300,000 human cases estimated to occur each year in the United States alone (Mead 2015). In North America, ticks carry a variety of pathogens in addition to Lyme disease spirochetes, including the rickettsia that cause Rocky Mountain spotted fever, anaplasmosis, and ehrlichiosis, and the viruses that cause Colorado tick fever and Powassan encephalitis, collectively causing thousands of additional cases of human illness each year. The Entomological Society of America issued a position statement on Tick-Borne Diseases in 2015 (http://www.entsoc.org/PDF/2015/ESA-PolicyStatement-TickBorneDiseases.pdf).

Worldwide, mosquitoes transmit pathogens that cause millions of cases of disease each year, with malaria and dengue of particular importance in tropical regions (Murray et al. 2012, Bhatt et al. 2013). In North America, thousands of cases of West Nile virus disease are reported yearly, with additional cases of Eastern equine encephalitis, St. Louis encephalitis, Lacrosse encephalitis, and other arboviral diseases (Reimann et al. 2008, Lindsey et al. 2010). The recent expansion and rapid geographic spread of dengue, chikungunya, and Zika viruses present new vector-borne disease threats for North America, particularly in southern regions (Brady et al. 2014, Vega-Rúa et al. 2014, Bogoch et al. 2016). Clearly, protecting human, livestock, and wildlife populations from vector-borne diseases, including by

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vector management, will be a major focus of public health and veterinary programs in the coming years.

Another serious problem that has become increasingly apparent in recent years is the decline of pollinators. Buchmann and Nabhan (1996) noticed the loss of populations of pollinating animals in southwestern North America, and identified habitat loss, pesticide use, and invasive species as factors likely contributing to these declines. Several studies have since documented declines in numerous taxa of pollinating organisms (Potts et al. 2010, Cameron et al. 2011, Goulson et al. 2015), and a National Academy of Sciences NRC report has addressed this issue (NRC 2007). A Presidential Memorandum issued in 2014 addressed the health of honey bees and other pollinators. In 2015 a federally appointed task force issued a Strategic Plan to Support the Health of Honey Bees and other Pollinators (https://obamawhitehouse.archives.gov/sites/default/files/microsites/ostp/Pollinator%20Health%20Strategy%20 2015.pdf, accessed 5 Jul 2017) and the Entomological Society of America released a position statement on Pollinator Health (http://www.entsoc.org/PDF/2015/ESA-PolicyStatement-PollinatorHealth.pdf, accessed 5 Jul 2017).

One topic that has not received sufficient attention is the possible impact of vector management on pollinator populations. Do current approaches to tick and mosquito management have adverse effects on pollinators? If so, how can vector management methods be targeted or modified to minimize any negative effects on pollinating species, while still protecting public health? Mosquitoes feed on nectar from flowers (Foster 1995), and can themselves be pollinators (e.g., Thien 1969, Gorham 1976); however, this issue will not be discussed in this report.

The North American Pollinator Protection Campaign (NAPPC) created a task force in 2014 to begin to address the issue of vector control and pollinator protection. NAPPC (http://pollinator.org/nappc/, accessed 5 Jul 2017) is a consortium of nongovernmental organizations, university professors, government agencies, companies, and industrial organizations that has been working for over 16 years to make progress toward conserving pollinators. There are clear differences in opinion and approach among the various individuals and groups represented within NAPPC, so the organization seeks areas where all parties can work together toward the goal of protecting pollinators. This paper reports the discussions of the Vector-Borne Disease and Pollinator Protection Task Force with regard to ticks and mosquitoes in particular, because of the major importance of these vectors in North America. We will focus our discussion specifically on management of ticks and mosquitoes to prevent pathogen transmission to humans, although much of our discussion would apply to management of these taxa for veterinary medicine and nuisance biting prevention as well. Task Force members are listed in the Acknowledgements. Our goal is to identify vector management methods that might adversely affect pollinating species, and consider methods of targeting or modifying vector management techniques so as to protect public health, while minimizing negative effects on pollinators.

Box 1
Tick management methods

- Self-protection precautions
  - behavioral
    - avoidance
    - protective clothing
    - tick checks
  - repellents
    - applied
    - treated clothing
- Habitat manipulation
  - leaf litter removal
  - prescribed burning
  - lawn mowing practices
  - woody plant thinning or clearing
  - barriers (wood chips, crushed rock, fencing)
  - selective plant removal
  - cleaning trail edges
- Manipulation of host populations
  - reproductive hosts (e.g., deer)
  - reservoir hosts (e.g., mice)
  - biodiversity manipulation
- Biological control
  - microbes
    - bacteria
    - nematodes
    - fungi
  - parasitoids
  - predators
    - invertebrates (e.g., ants)
    - vertebrates (e.g., guineafowl)
- Pesticides (characteristics of different chemical classes and formulations)
  - targeted applications
    - host-specific
    - temporal
    - spatial
  - broad-scale applications

Vector Management Practices

Numerous and diverse methods have been used for vector management, and novel techniques are under development. Tick control practices have recently been reviewed (Stafford and Kitron 2002, Ghosh et al. 2007, Piesman and Eisen 2008, Ginsberg 2014), and they include several categories of management methods (Box 1). Mosquito control methods (Box 2) include numerous traditional approaches, which were used for management of such diseases as yellow fever and malaria, as well as modern methods that help minimize negative environmental effects, and innovative new techniques that utilize genetic technology and mosquito-associated microbes (Pratt and Moore 1993, Rose 2001, Hoffman et al. 2011, Alphey 2014). Certain categories of tick and mosquito control methods appear most likely to have adverse effects on pollinators (Table 1). These methods fall into three main classes: 1) landscape manipulation for vector control, 2) introductions of predators, parasites, or pathogens to control vectors, and 3) pesticide applications.

Potential Effects of Vector Management on Pollinators

Landscape Manipulation

Effects on Floral Resources and Bee Nesting Habitat

Modification of wetlands to minimize larval mosquito habitat is an important feature of many mosquito control programs (Rey et al.

Box 2
Mosquito management methods

Larvae

- Habitat manipulation: water management
  - sanitation
    - clearing debris and objects that hold water
    - emptying bird baths, swimming pool covers, etc.
    - draining roadside ditches
    - proper design and modification of drainage sumps
  - modification of wetlands
    - channelizing streams
    - cleaning pond edges (e.g., clearing emergent vegetation, steepening edges)
    - drainage ditching
    - impoundments and sequestration ponds
    - open marsh water management
- Biological control
  - bacteria (e.g., *Bacillus thuringiensis israelensis*, *Lysinibacillus sphaericus*)
  - predators (e.g., *Gambusia*, *Fundulus*, and other predatory fish)
- Larvicides
  - insect growth regulators
  - oils
  - toxins

Adults

- Self-protection precautions
  - behavioral
    - avoidance
    - protective clothing
  - repellents
  - structural (screens, etc.)
- Trapping
- Reproductive manipulation
  - biological (e.g., *Wolbachia*)
  - genetic (e.g., Sterile Insect Technique, introducing favorable genotypes)
- Biological control (e.g., release of odonates, installation of bird or bat houses)
- Adulticides (characteristics of different chemical classes and formulations)
  - targeted applications
    - host-specific
    - temporal
    - spatial
  - broad-scale applications (e.g., to shut down epizootic)

2012), and could conceivably affect floral resources (e.g., entomophilous emergent plants and salt marsh species). Often these manipulations include modifications of artificial wetlands such as maintenance of water flow in roadside ditches and ensuring weekly draining of water collection sumps. Sanitation of artificial containers, clearing of rain gutters, and weekly dumping of containers such as bird baths to control container-breeding *Culex pipiens* L. (potential vector of West Nile virus) and *Aedes aegypti* L. (potential vector of dengue, chikungunya, and Zika viruses; Fauci and Morens 2016) also fit in this category. However, natural wetlands are also sometimes manipulated for mosquito control, and these activities can affect pollinator populations because wetlands can provide important bee forage (Starý and Tkalcu 1998, Moroń et al. 2008, Groff et al. 2016). The most widespread current manipulation programs of natural wetlands are probably salt marsh water management techniques that are designed to control salt marsh mosquitoes (e.g., *Ae. sollicitans* Walker) by minimizing water retention in puddles in the high marsh, and allowing fish access to ponds and puddles to control larvae (Wolfe 1996). Hydrologic manipulation of salt marshes could potentially affect populations of insect-pollinated (entomophilous) salt marsh plants (Smith et al. 2009), such as sea lavender (*Limonium carolinianum* (Walter) Britton), salt marsh fleabane (*Pluchea odorata* L. (Cassini)), marsh elder (*Iva frutescents* L.), and groundsel bush (*Baccharis halimifolia* L.). However, the effects would likely be idiosyncratic, depending on the effects of the specific water management program on the hydrology of the marsh being manipulated. Indeed, early mosquito ditching techniques apparently increased populations of *I. frutescens* by providing relatively dry berms along the sides of the ditches (Ferrigno 1970, Shisler 1973). Current marsh excavating equipment tends to avoid this by scattering sediment broadly on the marsh. To our knowledge, there have been no studies that specifically quantified the effects of open marsh water management practices on the availability of floral resources for pollinators.

Table 1. Vector control methods with potentially negative effects on pollinators

Class of control method	Possible effects
Landscape manipulation	Effects of habitat modification on floral resources or pollinator nesting habitat; effects on pesticide exposure when changes in habitats result in changes in pollinator distributions or dispersion patterns of pesticide residues
Biological control	Predation, parasitism, or infection of pollinating species
Pesticide applications	Direct mortality of pollinating species, effects on behavior, reproduction, overwinter survival, or resistance to pathogens

Planting of ornamentals, while beneficial to some pollinators, can sometimes serve as mosquito larval habitat. For example, *Ae. aegypti* readily breeds in artificial containers of water, including bromeliads (Chadee et al. 1998). Epiphytic bromeliads can potentially complicate management of *Ae. aegypti* in urban areas (Frank and Lounibos 2009), and can require intensive applications of larvicides on each plant (Crocker et al. 2017).

Habitat manipulation for tick control includes clearing of leaf litter (Schulze et al. 1995), removing lower vegetation and ground cover (Milne 1948, Hubálek et al. 2006), opening the tree canopy (Mount 1981), and controlled burning (Wilson 1986, Stafford et al. 1998). These practices would make conditions less favorable for some plant species, but more favorable for others, so the effects on pollinator resources would depend on local conditions and the specific manipulations applied. Similarly, because of the diversity of nesting habitat preferences by different bee species, these practices would vary in their effects on quality of bee nesting habitat. As in the case of wetland manipulation, the effects on pollinators would tend to be regionally specific, depending on local conditions. If a pollinator species of concern (e.g., a threatened or endangered species) is present in an area, these types of manipulations would have predictable effects on the suitability of the environment for that species and could be fashioned to avoid any negative effects.

Habitat management for tick vectors can also be coordinated with management of problem exotic and invasive vegetation because some invasives can provide optimal habitat for vector species such as *Ixodes scapularis* Say (Lubelczyk et al. 2004, Elias et al. 2006, Williams et al. 2009). Common practices for exotic plant reduction include herbicide application (foliar and stump treatment) and manual removal of target species (Flory and Clay 2009). Many exotic shrubs commonly targeted for removal, such as barberries (*Berberis* spp.) and Eurasian honeysuckles (*Lonicera* spp.) can also act as host plants for pollinators (Stubbs et al. 2007), so their removal may impact localized populations, while simultaneously reducing tick abundance (Williams et al. 2009). Exotics can sometimes provide important resources in otherwise disturbed systems with low floral diversity (Ghazoul 2002), so decisions about removal should balance the likely effects on both tick populations and resource availability for pollinators.

Effects on Exposure to Pesticides

Landscape manipulations for vector control could potentially modify the degree of pollinator exposure to pesticides by shifting pollinator habitat to sites near areas where pesticides are applied (with the potential for pesticide drift), or by modifying water flow patterns and thus movement patterns of pesticide residues. The net value of these types of manipulations for pollinators would depend on specific local considerations. For example, habitat modification to lower tick numbers by opening canopy and shrub vegetation to create drier conditions at ground level could result in increased floral abundance, which could improve pollinator habitat, but might also affect exposure to pesticide drift, depending on proximity to agricultural areas, local pesticide use patterns, and wind direction. Wetland manipulation might also affect dispersion of pesticide residues, although dilution of residues might be expected with water transport. Pollinators, especially in arid regions of North America, are likely to visit open-water wetlands for hydration or for nutrient and salt acquisition (Willmer and Stone 1997). It would be difficult to make general statements about the effects of these types of manipulations, because the implications for pollinator populations would depend on local distributions of pollinators, floral resources, and habitats.

Biological Control

Predators

Predator augmentation to control nuisance vectors, such as mosquitoes, can potentially pose a risk to pollinators. Vertebrates advocated for control of mosquitoes include fish, amphibians, birds, and bats (Chandra et al. 2008, DuRant and Hopkins 2008, Kunz et al. 2011). While 'stocking' of both fish and amphibians may have little effect on pollinators, management of birds or bats could potentially have both beneficial and negative effects on pollination in ecosystems. Indeed, some birds and bats (especially in southern regions) are themselves important pollinators (Buchmann and Nabhan 1996, Faegri and Van der Pijl 2013). Insectivorous birds and bats tend to be generalist predators, and because of the dramatic and rapid fluctuations in adult mosquito numbers (in response to variable environmental factors such as rainfall and ocean tides), these predators have difficulty tracking mosquito numbers, so experts generally do not consider them reliable biocontrol agents. There are few studies documenting impacts of insectivorous vertebrate populations on mosquito abundance in North America. Some studies in other regions of the world concluded that mosquitoes are an important prey item for bats (Gonsalves et al. 2013) and that some mosquito management activities might exacerbate declines in bat populations, but this possibility has not been well studied and effects on mosquito numbers have not been documented.

Attempts to manage mosquitoes by supplementing invertebrates has usually involved stocking of odonates (dragonflies and damselflies) into wetland systems, in an attempt to reduce larval mosquito populations (Stav et al. 2000, Shalaan and Canyon 2009). As top predators, it is surmised that odonates might readily use mosquito larvae as a food source (Kweka et al. 2011), and they might also affect pollinating species with aquatic larvae, such as midges. Results of stocking experiments are mixed, however, with some studies finding little effect on mosquito numbers, and others showing modest effects (less than fish or amphibians), and some showing that mosquitoes avoid ovipositing in water with predators present (Stav et al. 2000, Why et al. 2016). These studies mostly entailed artificial container experiments, limiting the ability to draw conclusions about efficacy in complex natural systems (Fincke et al. 1997). Finally, dragonflies have themselves been reported feeding on bees and butterflies, although we found no evidence in the literature that this predation affects population densities (Pritchard 1964, Alonso-Mejia and Marquez 1994). In addition, introduction of nonnative odonate species could have unforeseen adverse effects on local faunas.

Entomopathogens

Numerous pathogens have been developed or proposed for vector control, including viruses, bacteria, microsporidia, nematodes, and fungi (Samish et al. 2008, Kamereddine 2012). Nematodes and fungi have been developed as biocontrol agents for tick management, with the primary entomopathogen proposed for tick control in North America being the fungus *Metarhizium anisopliae* (Metchnikoff) Sorokin (Zhioua et al. 1997, Stafford and Allan 2010). This fungal species is broad spectrum and could potentially affect some pollinators, but effects vary among arthropod species (Ginsberg et al. 2002), and spores generally germinate under high humidity conditions (Benjamin et al. 2002), so applications can be targeted to minimize any negative effects on pollinating insects. To our knowledge, there have been no studies on possible effects of ground-level applications of entomopathogenic fungi on soil-nesting Hymenoptera. However, the entomopathogen, *Beauveria bassiana*, is commonly found naturally occurring in soil and twig nests of several species of solitary bees (Batra et al. 1973, Boomsma et al. 2014) and in nests of bumble bees (Macfarlane et al. 1995). The alfalfa leafcutting bee, *Megachile rotundata*, is a twig nesting solitary bee and is highly susceptible to some strains of *B. bassiana* (James et al. 2012). Entomopathogens, especially *Bacillus thuringiensis israelensis* Berliner (Bti) and *Lysinibacillus sphaericus* (Meyer and Neide), are widely used for control of larval mosquitoes (Lacey 2007). These bacteria display host specificity, with effects primarily on nematocerous Diptera (Lacey and Merritt 2003). Since they are applied to water to control larval mosquitoes, they would not be expected to affect pollinators. The one possible exception would be some dipteran species that have aquatic larval stages (Hershey et al. 1998) but that can act as pollinators as adults. It is not known whether area-wide applications might sometimes affect terrestrial species, although no mechanism for this type of effect seems likely.

Host Management

The impact to pollinators through control of vertebrate hosts of vector ticks or mosquitoes may be seen most immediately through manipulation or eradication of white-tail deer populations (Wilson et al. 1988, Rand et al. 2004). As the most common reproductive host for *I. scapularis* and *Amblyomma americanum* L. (Schulze et al. 2001), density of white-tail deer can affect the overall size of the tick population by providing increased bloodmeals for female ticks, although tick numbers can fluctuate widely beyond the effect of white-tail deer populations (Deblinger et al. 1993). In addition, white-tail deer provide bloodmeals for mammal-biting mosquitoes, such as *Cq. perturbans* and *Aedes vexans* Meigen (Molaei et al. 2008). Finally, deer can potentially act as reservoirs for mosquito-transmitted bunyaviruses such as Potosi virus and Cache Valley virus (Blackmore and Grimstad 1998).

Ecologically, white-tail deer have also assumed the role of a keystone herbivore, potentially altering forest vegetative composition through over-browsing (Waller and Alverson 1997). Studies examining the impact of browsing pressure on host plants for pollinators have shown mixed results, with some studies noting little difference in pollinator abundance associated with deer abundance (Vázquez and Simberloff 2004), while other studies (Balgooyen and Waller 1995) found potential impacts to pollinators following browsing of flowering species. Because insect densities are often correlated with host plant densities (Haddad et al. 2001), there is potential for negative effects on pollinators from higher deer density.

While studies have found that tick abundance decreases at densities below 10–20 deer/km^2 (Stafford et al. 2003, Rand et al. 2003), this is also the threshold above which white-tail deer are responsible for ecological changes in vegetative communities, which can themselves affect pollinators (Waller and Alverson 1997). Lowering deer densities, as a consequence, can potentially yield benefits to pollinators as host plants recover, especially for specialized pollinator species that target deer-preferred browse (Balgooyen and Waller 1995). As in the cases of biological control and habitat manipulation, the effects of vector control interventions on populations of nontarget organisms tend to be idiosyncratic, and attention to local conditions would be needed to assess effects on local pollinator species.

Pesticide Applications

Chemical Controls

Many chemicals can be used for vector management; this summary focuses on those used in the United States. Chemicals are divided into classes by mode of action/target, and mosquito control pesticides are further divided into larvicides or adulticides (http://www.epa.gov/mosquitocontrol, accessed 5 Jul 2017). Chemical controls can be natural or synthetic. We limit our discussion to active ingredients in each pesticide formulation as adjuvants/surfactants are not explicitly known (and their toxicity cannot easily be determined). However, a recent analysis suggests that some of these additives might have important effects (Mullin et al. 2015), so additional study of these chemicals is warranted.

Larvicides include the bacterial insecticides already mentioned (Bti, *L. sphaericus*, *Saccharopolyspora spinosa* Mertz and Yao), growth inhibitors (e.g., juvenile hormone mimics such as methoprene), organophosphates (temephos; discontinued), and surface agents (such as mineral oils and monomolecular films). Adulticides include organophosphates (chlorpyrifos, malathion, naled), pyrethrins, and synthetic pyrethroids (permethrin, resmethrin, sumithrin, prallethrin, etofenprox). Most pyrethroid formulations for mosquito control also include the synergist piperonyl butoxide. Adulticides for fleas and ticks can include fipronil, imidacloprid, and sometimes avermectins in addition to synthetic pyrethroids. Fipronil and avermectins are generally applied directly to the host, so these applications would not be expected to have broad effects on pollinators.

Numerous compounds are classified as "Minimum Risk Pesticides" and are exempted from pesticide registration by the EPA, including many that are used for vector control or as repellants. Examples include cedarwood oil, citronella, garlic oil, lemongrass oil, and rosemary oil (http://www.epa.gov/minimum-risk-pesticides, accessed 5 Jul 2017). The "minimum risk" designation refers to humans, and in general terms, to the environment, but not specifically to insect pollinators.

Environmental Hazards

Potential environmental effects of larvicides vary in different materials. Bacterial larvicides that use Bti and *L. sphaericus* are largely composed of bacterial toxins, although in some products bacterial growth and epizootic activity also occur (e.g., *L. sphaericus*). The toxicity of the Bti toxins to insects requires ingestion and depends on conditions within the gut (high pH and specific enzymes) that can activate the toxin (Jaquet et al. 1987). Such conditions are not common among all insects, making bacterial toxins relatively well-targeted insecticides. Spinosad, a product of the fermentation of *S. spinosa*, acts on the insect nervous system, and has broader spectrum activity against insects (Mayes et al. 2003, Williams et al. 2003). Juvenile growth hormone mimics are synthetic chemicals (e.g., methoprene, pyriproxyfen) that prevent expression of adult characters during molts, so that mosquitoes are unable to emerge as adults. These hormone mimics could potentially have activity against a wide variety of insects, depending on how they are applied, given that juvenile hormone plays roles in development and reproduction of virtually all insects. Diflubenzuron, which inhibits chitin production, is sometimes also used for control of mosquito larvae. Water surface films are synthetic products (mineral oils and monomolecular surface agents) that are applied to water bodies to coat the water surface, coating breathing siphons of mosquito larvae and interfering with water surface tension, preventing the larvae from remaining at the surface to get air. Other organisms with similar biological requirements (e.g., arthropods that need contact with the water surface for respiration) can potentially be similarly affected. All of these larvicidal products are generally applied directly to water bodies by hand, truck, airplane, or helicopter in order to target the aquatic stages of mosquitoes. As a result, the hazard they could present to pollinating insects is expected to be minimal because of the low exposure likelihood in treated water bodies. The exceptions are pollinating insects that have aquatic larval stages, such as some Diptera, and if there is some effect on pollinators drinking from the edges of water bodies.

The chemicals most commonly used to control adult mosquitoes as well as ticks and fleas fall largely within two classes of chemicals—organophosphates and pyrethroids (some other classes of chemicals, including carbamates and avermectins, are sometimes used as well). Organophosphate chemicals (OPs) were first formulated in the mid-1800s (triethylphosphate then tetraethylpyrophosphate; Soltaninejad and Shadnia 2014), and many were later developed for insecticidal uses. Pyrethroid insecticide use began to increase partly because of concern for OP exposures to humans through occupational and residential uses for a broad array of agricultural and home pests. Pyrethroid insecticides are based on the chemical constituents in extracts of *Chrysanthemum* flowers (pyrethrin, cinerin, and jasmolin) that have insecticidal properties. Synthetic pyrethroids were developed to have insecticidal properties similar to the natural compounds, but to also have greater environmental stability to improve efficacy. Organophosphates and pyrethroids are both neurotoxins, but with different modes of action; organophosphates are acetylcholinesterase inhibitors while pyrethroids are sodium channel blockers (e.g., see Insecticide Resistance Action Committee website, http://www.irac-online.org/, accessed 5 Jul 2017). Because of the different modes of action of these two classes, application strategies can be designed to avoid the evolution of resistance to these materials in vectors.

The risks to pollinators presented by pesticides used for disease vector control depend upon the toxicities, targeting of applications, and environmental fates of those pesticides. The U.S. Environmental Protection Agency characterizes pesticides in terms of relative toxicity to different ecological receptors, including birds, aquatic organisms (fish and invertebrates), wild mammals, and nontarget insects. With respect to honey bees, the categories are 1) highly toxic when the acute toxicity value (LD_{50} from acute contact testing, OPP 850.3020) is < 2 μg/bee, 2) moderately toxic when the LD_{50} is between 2 and 10.99 μg/bee, and 3) practically nontoxic when the $LD_{50} \geq 11$ μg/bee. The organophosphates chlorpyrifos, malathion, and naled, and most of the pyrethroids and pyrethrins, along with imidacloprid and fipronil, are categorized as highly toxic to honey bees with direct exposure (Table 2). A categorization of practically nontoxic was assigned to the bacterial toxin from a subspecies of *Bacillus thuringiensis* (*kurstaki*). The toxicity of methoprene to honey bees was not reported by the USEPA. While the honey bee acute toxicity data for select insecticides summarized in Table 2 might be useful as a guide or "rule of thumb" for toxicity to a local bee community, recent research has shown that while modes of action are the same among bee species, toxicities vary greatly. For instance, Sanchez-Bayo and Goka (2014) reported that honey bees are considerably more sensitive to permethrin than bumble bees (*Bombus spp*.) but less sensitive to carbaryl. Biddinger et al. (2013) found honey bees to be far less sensitive to the neonicotinoid insecticide, acetamiprid, than *Osmia cornifrons* (Radoszkowski), but sensitivity to the neonicotinoid imidacloprid was reversed, the honey bee being far more sensitive than *O. lignaria* Say. Thus, while the large volume of accumulated data on honey bee toxicity to insecticides is useful, these data cannot be directly applied to the native bee community or to other pollinators in North America. Toxicities of insecticides to native bees and other wild insect pollinators are important areas for future research.

The possible effects of "minimum risk pesticides" on pollinating species have received little attention. Plant-derived essential oils have been proposed for management of mosquito larvae (e.g., Amer and Mehlhorn 2006, Pitasawat et al. 2007) and ticks (e.g., Dolan et al. 2009, Jordan et al. 2011). Several plant-derived, or "natural" products have relatively low toxicity to honey bees and some can be used for control of pathogens and pests of honey bee colonies (e.g., Melathopoulos et al. 2000, Flesar et al. 2010). Nevertheless, given the broad taxonomic range of species that can serve as pollinators, it seems plausible that natural products that are toxic to mosquitoes or ticks would also be toxic to at least some pollinator species. Furthermore, application of these products in residential settings for tick control could result in exposure of pollinators on lawns (for example, bees visiting dandelion, clover, gill-over-the-ground, etc.) or on flowers blooming at forest edges. Applications along roadsides could also result in exposure of flower-visiting insects. Possible negative effects of these pesticides on pollinators, and strategies to avoid these effects, are worthy of future study. The terms "minimum risk" or "natural" do not necessarily imply safety for pollinators.

Many commonly used pesticides are themselves natural products and are clearly toxic to pollinators. Examples include pyrethrin (from *Chrysanthemum*) and spinosad (produced by the soil actinomycete, *S. spinosa*), which is toxic to honey bees and bumble bees (Thompson et al. 2000, Morandin et al. 2005). In addition, the "natural" material, nootkatone (from grapefruit and Alaska yellow cedar) has potential for vector control (e.g., Flor-Weiler et al. 2011), but nontarget effects have not been well characterized.

Environmental Fate of Larvicides

Larvicides are applied as liquid or granular formulations directly to water using backpack sprayers, truck or aircraft mounted sprayers, or by hand dispersal as solid tablet or briquet formulations. Application directly to water results in minimal exposure to pollinators, except possibly for those with aquatic larval stages. Exposure is plausible when adult pollinators drink from treated waters, but the larvicides generally used for mosquito control (bacterial products and insect growth regulators) are relatively nontoxic to adult pollinators.

The bacterial larvicide Bti degrades when exposed to UV light. Its half-life under normal sunlit conditions is 3.8 h. It can be effective for up to 48 h in water, after which it gradually settles out or adheres to suspended organic matter (http://pmep.cce.cornell.edu/profiles/extoxnet/24d-captan/bt-ext.html, accessed 5 Jul 2017). Aqueous photolysis of spinosad occurs in natural sunlight, and is the primary route of degradation in aquatic systems (http://www.cdpr.ca.gov/docs/emon/pubs/fatememo/spinosad_fate.pdf, accessed 5 Jul 2017). Some solid formulations release spinosad slowly into the water, ensuring low acute exposures.

Methoprene also degrades in sunlight (https://www3.epa.gov/pesticides/chem_search/reg_actions/reregistration/fs_PC-105401_1-Jun-01.pdf, accessed 5 Jul 2017) and is expected to sorb to suspended solids and sediment in soil, although deployment in slow-release pellets can result in relatively long half-lives in water (http://www.cdpr.ca.gov/docs/emon/pubs/methofate.pdf, accessed 5 Jul 2017). Physical characteristics of many aquatic environments promote dilution, adsorption on particles, dissipation, etc., of larvicides. Therefore, most larvicides used for mosquito control are not likely to last long enough for major nontarget effects on pollinators, except for specific cases where aquatic larvae of pollinating species (e.g., some midges and syrphids) are exposed (especially when there is repeated use in the same site).

Environmental Fate of Adulticides

Adulticides are applied by aircraft, truck-mounted, or backpack sprayers as thermal fog or ULV (ultra-low volume) formulations that dispense extremely fine aerosol droplets (one quarter to 3 fl oz of active ingredient/acre [3 oz a.i./A]), or as foliar sprays or granular formulations. Ultra-low volume and foliar sprays can pose a risk to pollinators, as any insect near them or that visits the plants that are sprayed will be exposed. Granular applications are less likely to affect pollinators as they visit flowers but could potentially affect ground nesting bees if they are applied at or near nesting sites. Broad-scale applications are more likely to affect pollinators than targeted applications, and targeting strategies offer some potential to maintain effective vector control, while minimizing nontarget effects on pollinating species.

Most compounds used for foliar applications (organophosphates, pyrethroids) are expected to dissipate over several days (Table 2), by leaching and degradation. However, compounds that end up in the soil could persist longer (weeks to months).

Table 2. Characteristics of adulticides commonly used for vector control in the United States

Chemical	Bee toxicity	Physical chemical properties		Persistence DT_{50} (d)		
	Honey bee (*A. mellifera*) Contact LD_{50} (µg/bee)[a]	Aqueous solubility (mg/L at 20 °C)[b]	Mobility log organic carbon partition coefficient (log K_{oc})[b]	Foliar[b]	Soil[b]	Aqueous photolysis[b]
Organophosphates						
Chlorpyrifos	0.010–0.0114	1.05	3.9	7.0	50	30
Malathion	0.27–0.709	148	3.3	5.9	0.17	98
Naled	0.480	2000	2.2	1.0	1	4.4
Pyrethroids						
Bifenthrin	0.015	0.001	5.4	5.4	26	255
Deltamethrin	0.067	0.0002	7.0	5.4	13	48
Etofenprox	0.015	0.023	4.2	2.1	11	6.3
Permethrin	0.024–0.16	0.2	5	8.1	13	1
Resmethrin	0.063	0.01	5.0	NA	30	NA
Phenothrin/Sumithrin	0.067	0.0097	5.2	6	≤1	6.5
Prallethrin	0.028	8.03	NA	3.0	NA	NA
Pyrethrins	0.022	NA	NA	NA	1-2	<1.0
Pyrethroid synergist						
Piperonyl butoxide	>1125[c]	14.3	2.6–3.1[c]	1.6	13	<1[c]
Systemic insecticides						
Imidacloprid	0.044–0.078	610	2.1–2.5[d]	3	191	0.2
Fipronil	0.0034–0.013	3.78	2.9[e]	3	142	0.33

[a] USEPA Ecotox Database https://cfpub.epa.gov/ecotox/.
[b] University of Hertfordshire Pesticide Properties Database http://sitem.herts.ac.uk/aeru/ppdb/en/, http://npic.orst.edu/factsheets/dphengen.html, http://www.who.int/whopes/quality/en/dPhenothrin_WHO_Evaluation.pdf.
[c] USEPA. 2010. EFED Registration Review Problem Formulation for Piperonyl Butoxide (PBO).
[d] California Department of Pesticide Regulation Environmental Fate of Imidacloprid, http://www.cdpr.ca.gov/docs/emon/pubs/fatememo/imid.pdf.
[e] California Department of Pesticide Regulation Environmental Fate of Fipronil, http://cdpr.ca.gov/docs/emon/pubs/fatememo/fipronilrev.pdf.

The organophosphate naled quickly undergoes aqueous photolysis, although a major breakdown product is dichlorvos, which is a registered insecticide (and is highly toxic to honey bees on an acute exposure basis). Both malathion and naled degrade in soil, with half-lives in soil on the order of days (Table 2). Chlorpyrifos is more persistent on leaves and in soil than naled or malathion. It is used in Mexico and in some U.S. locations, but is not used in foliar sprays for vector control (Table 2).

Pyrethrins degrade quickly in sunlight (<1 d, USEPA 2006), and are inactivated and decomposed by exposure to light and air (EXTOXNET 1994). Synthetic pyrethroids tend to be more stable than natural pyrethrins, though they are generally expected to persist in the environment for less than one month (Table 2). Pyrethroids sorb strongly to soils, and are not likely to be transported in the aqueous phase.

Imidacloprid and fipronil are systemic insecticides, and they can be taken up by plants and into plant tissue including pollen. Likely routes of exposure via this contamination route (through pollen, guttation drops, etc.) is from coated seeds used in agriculture and not via vector control sprays. Imidacloprid and fipronil photodegrade quickly in shallow water but can persist in soils (Bonmatin et al. 2015, Table 2). However, most uses of systemics for vector control involve direct application to animal hosts, which are not likely to result in substantial contamination that would affect pollinators.

Targeting Pesticide Applications

Careful targeting of pesticide applications offers considerable potential to minimize negative effects on pollinators, while providing effective vector control and public health protection (Table 3). Note that many of these practices are already commonly utilized to target vectors (indicated by superscripts in Table 3), and have the additional benefit of minimizing pollinator exposure. The specific approach to targeting applications should be tailored to details of local transmission patterns, but several generalities are possible. For example, pesticides with short environmental persistence offer the possibility of temporal targeting: applications are timed to maximize vector mortality, and for pesticides to dissipate before pollinators are active. Therefore, for ULV applications, shorter half-life chemicals would be preferable for pollinator protection than longer-lived materials. An example would be ULV applications of short-lived synthetic pyrethroids at night to control night-active vector species such as *Cx. pipiens* (Suom et al. 2010), allowing dispersion and degradation of pesticide before peaks of pollinator activity the following day. Caron (1979) found adverse effects on honey bees of daytime ULV insecticide applications, but no discernable effects of nighttime applications. This approach would not prevent exposure of night-flying pollinators such as sphingid moths (Baker 1961), stages of insects exposed on vegetation (e.g., caterpillars), or possibly pollinating species that sleep in or on flowers (Banks 1902). Of course, spatial targeting (to avoid known concentrations of pollinating species) could complement the temporal targeting.

Approaches to spatial and temporal targeting of pesticide applications are summarized in Table 3, according to characteristics of the vectors to be controlled. These are general classes of vectors, and specific targeting approaches would depend on local details of geography, demography, and transmission patterns. For example, spatial targeting could be useful to avoid negative effects from applications to control day-flying species, such as *Ae. aegypti*. Outbreaks of diseases caused by viruses and transmitted by *Ae. aegypti*, such as dengue, chikungunya, and Zika, typically occur in urban areas, or in nonurban residential areas, because this species lives in close association with humans, especially in and around human dwellings, resulting in a very efficient human to mosquito to human transmission pattern. Targeting pesticide applications at human residences

Table 3. Approaches to targeting pesticide applications to avoid negative effects on pollinators

Vectors	Example	Targeting approach	Pathogens
Mosquito larvae			
Container species	*Aedes aegypti*	Artificial and natural containers[a]	DENV, ZIKV
	Aedes albopictus		
	Aedes triseriatus		LACV
Stagnant pool species	*Culex pipiens*	Catch basins, containers,[a] use vector-specific materials in stagnant pools[a]	WNV
Salt marsh species	*Aedes sollicitans*	Temporal timing of juvenile hormone mimics to 4th instar	EEEV
Mosquito adults			
Crepuscular mosquitoes	*Aedes vexans*	ULV application at sunset,[a] avoid flower patches	WNV, EEEV
Nocturnal mosquitoes	*Culex pipiens*	ULV application after sunset[a]	WNV
Diurnal mosquitoes	*Aedes aegypti*	Targeted applications in and near residences,[a] avoid flower patches and bee nesting sites	DENV, ZIKV, CHIKV
Ticks			
Forest ticks	*Ixodes scapularis* nymphs, adults	Granular formulations, restrict spray applications to trails and leaf litter	Lyme borreliae
Open-habitat ticks	*Dermacentor variabilis*, *I. scapularis* adults	Target trails and paths, avoid flower patches or apply short half-life material at night	Spotted fever rickettsiae, Lyme borreliae

[a] These practices are often already followed for specific targeting of vectors, but also minimize exposure of pollinators to pesticides.
DENV, dengue virus; ZIKV, Zika virus; LACV, LaCrosse virus; WNV, West Nile virus; EEEV, Eastern equine encephalitis virus; CHIKV, Chikungunya virus.

can minimize negative effects on wild pollinators in natural areas, although wild pollinator species living in urban environments (Matteson and Langellotto 2010, Lowenstein et al. 2015, Sirohi et al. 2015) might still be affected.

Technical approaches to minimize nontarget effects of aerial applications for mosquito control include computerized systems in aircraft that take air movements into account to optimize targeting of applied materials, application equipment that ensures droplet sizes that minimize settling (allowing effective targeting of flying mosquitoes, while minimizing exposure of ground-dwelling arthropods; e.g., Zhong et al. 2004, Schleier et al. 2008, Peterson et al. 2016), and use of short half-life materials to avoid long-term residual effects. However, some targeting issues remain, especially as related to effects of pesticide drift and of environmental mobility of residues. For example, Long and Krupke (2016) recently detected phenothrin and prallethrin, which are synthetic pyrethroids, in floral pollen in agricultural and nonagricultural sites in Indiana. Evidence suggests that these products were used for household and yard pests in the study area and not for vector control (K. Larson, personal communication), and the source and mode of transport of these residues remain unclear. Nevertheless, drift can be an issue with aerially applied materials (Davis and Williams 1990, Hennessey et al. 1992), and should be considered in targeting of applications to avoid exposure of pollinators.

Specific knowledge of the spectrum of activity of different pesticides and formulations can be used to target applications to effectively control vectors while minimizing effects on vulnerable pollinator species. For example, ULV application of pyrethrins for mosquito control tended to have greatest nontarget effect on small-bodied arthropods and relatively little effect on large-bodied species (Boyce et al. 2007, Kwan et al. 2009), effects of truck-based ULV adulticide applications with distance have been characterized (Rinkevich et al. 2017), and several studies have provided detailed assessments of the effects of naled and permethrin applications on butterflies (Zhong et al. 2010, Hoang et al. 2011, Bargar 2012, Hoang and Rand 2015). Along with knowledge of local pollinator faunas, this information can aid in targeting applications to minimize nontarget effects.

Different application modalities have specific risks in terms of pollinator exposure. For example, truck sprayers apply pesticides along roadsides, which can pose particular risks of exposure to pollinators on roadside plants. This potential risk can be lowered by temporal targeting (e.g., utilizing truck sprayers with short-lived chemicals primarily at night), or spatial targeting (e.g., using truck sprayers primarily in urban areas). Granular applications for tick management, though well targeted to avoid pollinating insects on flowers, could potentially harm soil-nesting pollinators, such as many bees and wasps. Spatial targeting to avoid known nesting sites could help avoid this possible route of exposure. Finally, notification procedures can protect domesticated bees from pesticide exposure. Many mosquito management programs have "beekeeper lists" that can help avoid honey bee mortality from pesticide applications for vector control. The risks from specific modalities of pesticide application are varied and numerous, and depend on local conditions. In planning vector control applications, attention can be paid to specific local conditions that might result in pollinator mortality from pesticides, so that applications can be targeted to minimize exposures.

Considerations for Vector Control Programs

Information Needs: Considering Effects on Pollinators in the Planning and Design of Vector Management Programs

Information on local pollinator phenologies and distributions should be made available to those designing local vector management programs, and considered in program design. The extent to which vector control measures adversely impact pollinators often depends on local factors. Examples include the seasonal activity patterns of pollinators and flowering phenologies in relation to the seasonality of local vectors and pathogens, and the locations of important floral resources and pollinator nesting habitat in relation to vector production sites and areas of encounter between vectors and people.

Utilizing this information in the planning of vector management strategies can allow targeted management that minimizes negative effects on pollinators. However, this type of information is rarely considered in vector control programs.

Some current practices already target control measures in such a way as to minimize adverse effects on pollinators. For example, in most northeastern U.S. locations mosquito control emphasizes larval management early in the season, which presumably has minimal effect on the numerous solitary and primitively social bee species that are active in spring through midsummer. Aerial pesticide applications occur mostly at or after dusk in late summer, when epizootic activity of mosquito-borne viruses such as West Nile virus and Eastern equine encephalitis virus and potential human exposure are greatest, and fewer bee species are active. However, some pollinator species, including honey bees, bumble bees, and some species of univoltine solitary bees, are active in late summer, and identifying likely locations of pollinator activity and nesting sites can help direct any needed aerial applications to avoid unnecessary pollinator mortality. Applications that affect pollinators might sometimes be needed to protect public health, but these necessary applications could be reduced with careful planning, and pollinator mortality resulting from lack of awareness could be avoided.

Targeted Management: Efficient Management of Vector-Borne Pathogens

There is general agreement that human disease should be minimized, and that natural areas should be protected. One way to accomplish these goals simultaneously is to manage vector-borne diseases as efficiently as possible. From the perspective of pollinator protection, efficient and well-targeted management minimizes the necessity for large-scale applications of broad-spectrum pesticides. Such applications, which can potentially cause substantial mortality of pollinators, would be needed only rarely (for example, to prevent a rapidly growing epizootic of a dangerous pathogen from causing an epidemic) in an efficient management program. From the public health perspective, efficient management implies efficient use of resources, so that with a given level of intervention, fewer people get sick. This perspective allows vector control specialists to work with conservation professionals and pollinator experts to jointly develop vector control programs that optimize both goals.

Research Needs: Research to Improve Management of Vectors While Minimizing Adverse Effects on Pollinators

One important area of research is decision-making in vector management. Most vector management decisions should be made in an Integrated Pest Management (IPM) context (Entomological Society of America 2016), which involves surveillance and integration of various approaches to minimize the number of human cases of vector-borne disease. Similar approaches to natural resource management include Adaptive Management approaches (which are very similar to many IPM programs) and Structured Decision Making to develop management plans (Runge et al. 2013). Integration of multiple approaches provides an opportunity to foster approaches that minimize negative effects on pollinators, while simultaneously optimizing protection of public health. The traditional theory of IPM was developed for agricultural pests and not for vector-borne pathogens. Integrated Vector Management (IVM) programs differ in specific criteria for management decisions from agricultural IPM programs (Matthews 2011, Ginsberg 2014). Decision making for vector management would benefit from the development of theoretical approaches to efficient management, which can also consider nontarget effects, such as effects on pollinators. Transmission patterns of vector-borne pathogens have been extensively modeled, and these models can often be adapted to help plan specific management programs. For example, Ogden et al. (2005) developed a simulation model for tick populations and transmission of Lyme spirochetes, and Morin et al. (2015) developed an SEIR (Susceptible-Exposed-Infectious-Recovered) model to study the effects of precipitation and temperature on dengue transmission. These models could be modified to consider the effects of specific control methods, alone and in combination, on pathogen transmission, and the effects of the various possible combinations of control methods on pollinator populations could be assessed. Indeed, some integrated vector management programs already utilize this type of approach (especially for mosquito control), in that they tie interventions to surveillance data, and target interventions based on the level of risk to human health. However, these programs rarely consider effects on pollinators in program design. Additional attention to decision-making in vector control can better optimize integration of management techniques, while simultaneously considering potential effects on pollinators. This approach would allow comprehensive planning that could explicitly consider nontarget effects in vector management programs.

Research and development on finely targeted approaches to vector and pathogen management show considerable promise. Examples include genetic approaches to management of target species, including sterile insect techniques and gene or protein targets revealed from genomic studies of important vectors (e.g., Alphey 2014, Gulia-Nuss et al. 2016), species-specific microbial control methods such as manipulation of *Wolbachia* in vectors (e.g., Hoffman et al. 2011, Bian et al. 2013), and trapping technologies that target individual species of importance (e.g., Lorenzi et al. 2016, Barrera et al. 2017). Some of these approaches involve novel manipulations of species, which could potentially have unanticipated effects on natural systems. They should therefore be carefully studied, applied with caution, and evaluated by ecologists with comprehensive knowledge of natural systems to avoid unexpected consequences. Nevertheless, they show promise for finely targeted management in the future.

Another important topic for future research is to document the effects of specific vector control methods on populations of pollinators. Comparative studies of effects on pollinating species of alternative approaches to vector management (e.g., effects of different pesticide formulations, or the comparative effects of environmental manipulations vs. pesticide applications), would be valuable. Documenting the effectiveness for vector control, and the nontarget effects of "natural" and "minimum risk" pesticides is of interest, in view of the potential for widespread residential use of these products.

Implementation: Collaborative Programs to Effectively Control Vector-Borne Pathogens While Minimizing Negative Effects on Pollinators

The importance of local conditions in determining effective approaches to vector control, and also potential effects of vector control on pollinators, means that local collaborations are needed in which vector management professionals work with pollinator experts. Some examples of these types of collaborative programs exist. One example is the collaborative relationship between Suffolk County Vector Control and Fire Island National Seashore in New York, which includes a consultation process between the park and vector control agency in cases when surveillance suggests a possible disease risk (Dillon 2000). Additional examples include notification programs that help increase communication between applicators and beekeepers. However, there is no standardized mechanism to develop these collaborative bodies to co-optimize vector control and pollinator protection efforts.

One obstacle is the number and variety of agencies responsible for vector management, which can include state public health agencies, departments of environmental conservation, similar agencies at the county and local level, and sometimes departments of public works and local parks. Similarly, conservation agencies can be federal, state, county, or local institutions, and often nongovernmental groups are important contributors to local practice. Therefore, it is often not clear which groups would be appropriate partners in a collaborative planning process for vector management. Nevertheless, these collaborations offer the possibility of improving the success of vector-borne disease management programs while avoiding negative effects on pollinating species. Several states currently have pollinator protection working groups, which can facilitate collaborative programs that provide information and expertise to state and local vector control programs. Furthermore, some organizations, such as the National Association of State Departments of Agriculture (NASDA), the Xerces Society (Mazzacano and Black 2013), and the Pollinator Partnership, have issued documents that can provide useful information. Guidelines for both vector management and pollinator protection that can help provide frameworks for local collaborations are available online from numerous sources, such as the American Mosquito Control Association (https://amca.memberclicks.net/assets/HomePage/amca%20guidelines%20final_pdf.pdf), Centers for Disease Control and Prevention (http://www.cdc.gov), Xerces Society (http://xerces.org/pesticides/mosquito-management-wetlands/), National Association of State Departments of Agriculture (http://www.nasda.org/pollinators.aspx), and several state and locally focused sources (e.g., http://westnile.ca.gov/resources.php, http://consensus.fsu.edu/mc/, http://www.ct.gov/caes/lib/caes/documents/publications/bulletins/b1010.pdf, http://www.dem.ri.gov/programs/agriculture/pollinator-working-group.php). Differences of approach between vector control and pollinator protection efforts are common. Collaborative programs, in which everyone understands the values and objectives of all stakeholders, as well as the mandates and constraints under which all participants work, can help optimize results in terms of both pollinator protection and public health.

Conclusions

- Vectors and pathogens of public health importance vary in different locations, as do populations of pollinators and floral resources. Therefore, knowledge of both vector-borne pathogens and local pollinators are needed to minimize negative effects on pollinators of any vector control program. Combining these areas of expertise is likely to be most effective at the planning stages of vector management programs.
- Efficient targeting of management interventions can help simultaneously help protect public health and minimize adverse effects on pollinator populations.
- Research on decision-making in vector control can improve efficiency of management programs. In particular, models that can help optimize integration of control methods, while simultaneously predicting effects on nontarget organisms, can aid decision-making for both vector-borne disease management and pollinator protection.
- Research on finely targeted approaches to vector and pathogen management, such as trapping, genetic techniques, and manipulation of microbes that affect vectors, can provide additional tools for vector management that can minimize effects on pollinators. Study of possible indirect ecological effects of these methods is important before broad implementation.
- Research on effectiveness and nontarget effects of specific control methods, including both traditional control methods and natural or minimum risk methods, will help in the design of vector management programs that minimize adverse effects on pollinators.
- Implementation of these integrated management programs will require novel collaborations between vector control agencies and experts on pollinators. Establishment of these collaborative groups is challenging because responsibility for vector management varies in different locations (e.g., county or state agencies, departments of public works, pest control companies, homeowners), and pollinator expertise varies in different locales (e.g., university or government scientists, staff members of conservation or land management organizations). Fortunately, guidelines for vector management programs and best practices for pollinator protection, which can help in establishing these collaborations, are available online from numerous federal and state government agencies, as well as from professional vector control and conservation organizations.

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