Integrated Pest Management of Mosquitoes

A Case Study of West Nile Virus in California

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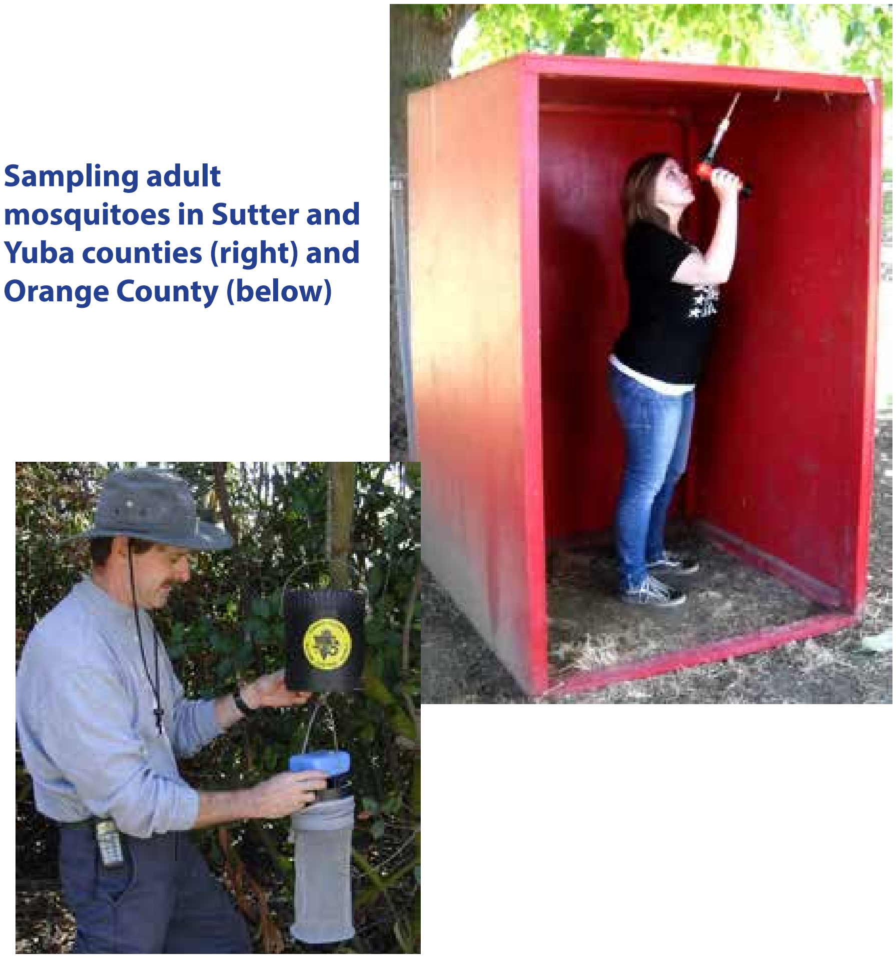
EXECUTIVE SUMMARY

Here we present case studies of three mosquito control districts in California following the rapid expansion of West Nile virus in California. The districts include urban centers and rural areas. This report documents how the districts use all available integrated pest management tools, and how the districts develop and deploy new tools and technologies that improve their ability to minimize the exposure of humans and the environment to mosquitoes and the products used to control them and minimize the cost of the programs. District outreach through printed and electronic media and in-person participation at community events successfully prevents mosquito bites and transmission of disease by raising awareness. Outreach efforts increase dead bird submissions to the dead bird surveillance program that in turn leads to better monitoring of virus activity in bird populations. Districts employ improved sampling strategies, crowdsourcing, and geographic information systems (GIS) to pinpoint areas of West Nile virus risk and target these areas with higher precision. Higher precision leads to the effective reduction of mosquito populations, and reduced costs and reduced environmental and human exposure to pesticides. Districts are actively involved in continued study of new surveillance methods, and the relationship between surveillance data and the risk of human disease — this relationship is used to make decisions about suppression activities such as pesticide applications. Although the current control methods have been shown to have low environmental and human health impacts, public resistance to the use of some products such as pyrethroids and organophosphates necessitates the discovery of new materials for mosquito management. Mosquito resistance to pesticides used to control them is another important reason to discover new management products. The *Wolbachia* bacterium is one such management tactic that is in the process of being registered in the United States. If demonstrated to be successful, this product could be an important new tool in the fight against mosquitoes and the diseases that they carry. Finally, education about the concept of risk associated with pesticide use and mosquitoes is necessary to insure that the risks and benefits associated with vector control are broadly understood.

Encephalitis mosquito (Joseph Burger, Bugwood.org)

Northern house mosquito (Susan Ellis, Bugwood.org)

Sampling adult mosquitoes in Sutter and Yuba counties (right) and Orange County (below)



INTRODUCTION

There are 72 mosquito control districts covering most of California. Many were created more than a century ago to protect people from the risks associated with mosquitoes. The control efforts were first directed against vectors of malaria (*Plasmodium vivax*), an endemic disease in California transmitted by the western malaria mosquito (*Anopheles freeborni*) (Reisen 2012). While malaria no longer poses a public health threat in California, mosquitoes remain a nuisance pest and a public health risk because they transmit viruses that can cause encephalitis such as West Nile virus (Reisen et al. 2008).

The context in which the districts function and the communities they serve have changed over the past century. The population in California has expanded from nearly 2.4 million in 1910 to over 39 million in 2016. Education levels, indicated by the proportion of residents with a bachelor's degree or higher, have been increasing over the past decade. The expansion of the Internet has made data and information more accessible. An increasing population with higher levels of education and increased access to information, coupled with increasing concerns about pesticide use and environmental impacts, means that districts are under increasing pressure to minimize the risks posed by pesticides to human and environmental health and at the same time continue to manage mosquitoes effectively with tightening budgets. To simultaneously control costs and minimize both the risks posed by the mosquitoes and the risks posed by mosquito-management tactics to human and environmental health, the districts use integrated pest management.

We present case studies of three mosquito control districts in California following the rapid expansion of West Nile virus in California in the early 2000s. The case-study format was chosen because the districts efforts to manage mosquito populations are specific to the communities they serve (Mirriam 2009). Districts must align their efforts with the values and goals of the communities they serve and management tactics used in one district may not be publicly acceptable in another.

We focus here on three districts representing two urban centers and three rural counties within California: Sacramento-Yolo, Orange, and Sutter-Yuba. They were chosen because of the incidence of West Nile virus outbreaks, the availability of information on disease impact, and the availability of data and information about their control programs. These three districts also demonstrate how different districts must balance the public perception of the risks posed by mosquitoes and the materials used to control those mosquitoes. West Nile virus was chosen because it has been an important driver of mosquito control in California today.

This report documents the many integrated pest management tools used by the three districts, and how recent changes in decision-tools, mapping and surveillance, area-wide management, and outreach, have further reduced the exposure of humans and the environment to mosquitoes and the products used to control them.

Data sources used for this report included: Center for Disease Control (cdc.gov), Census Bureau (www.census.gov), USDA National Agricultural Statistics Service (www.nass.usda.gov), California Pesticide Use Reporting database (ziram.lawr.ucdavis.edu/PURwebGIS.html), California Department of Public Health (www.cdph.ca.gov), California Health and Human Services Agency (www.chhs.ca.gov), Mosquito and Vector Control Association of California (www.mvcac.org), and California Department of Agriculture (www.cdfa.ca.gov), and the California Irrigation Management Information System (CIMIS).

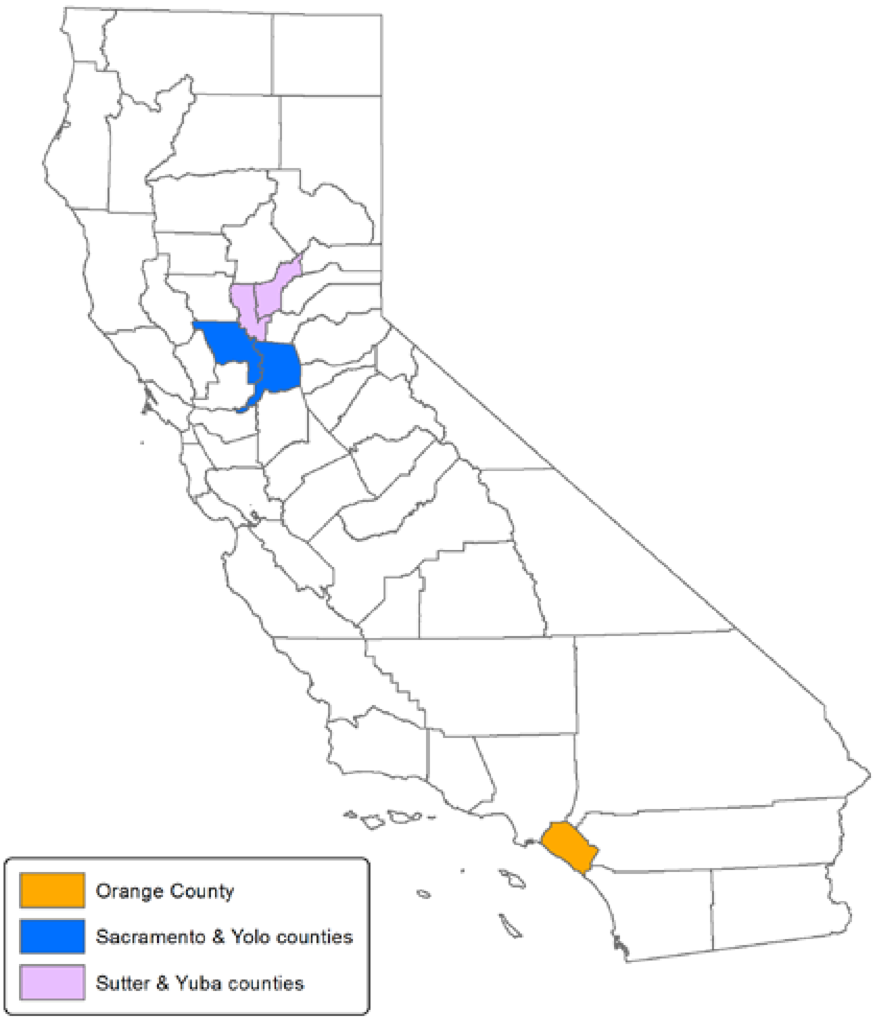


Figure 1. Location of mosquito and vector control districts included in this case study

BACKGROUND INFORMATION

Mosquito Control District Overviews

The Orange County Mosquito and Vector Control District protects more than 3.1 million residents in the largely metropolitan area of 791 square miles. The district is bordered by Los Angeles County to the north and San Bernardino and Riverside counties to the east and San Diego County to the south (Figure 1). Orange County is considered to be part of the greater Los Angeles metropolitan area. Orange County's climate is typically maritime Mediterranean, with mild winter temperatures and warm, dry summers moderated by easterly winds from the Pacific Ocean. The mean annual temperature is 65 F and an average of 14 inches of rain fall annually. On average, measurable rainfall occurs on 22 days per year. Nearly 38% of the population in the county possesses a bachelor's degree or higher. Very little agricultural activity occurs in the county. Nursery production is the predominant agricultural activity followed by limited fruit and vegetable production that covers nearly 3,500 acres (2015 Orange County Crop and Livestock Report accessed through the California Department of Food and Agriculture). The Orange County district had the highest number West Nile cases in California in 2014 with 280 cases and nine deaths (Nguyen et al. 2015).

The Sutter-Yuba Mosquito and Vector Control District protects most of Sutter County and about half of Yuba County, covering 706 square miles and about 130,000 residents. The largest city in the district is Yuba City with 68,000 inhabitants. The majority of the district is on the Sacramento Valley floor where gentle flatlands typify the topography. The district is bordered by Butte, Plumas, and Sierra counties to the north, Nevada County to the east, Sacramento, Yolo and Placer counties to the south, and Colusa County to the west (Figure 1). The confluence of the Sacramento and Feather rivers runs next to Yuba City. The climate is generally Mediterranean with hot, dry summers — high temperatures in summer average 90 F. Prevailing winds are moderate and predominantly from the south. In winter, daytime highs average 50 F and night time temperatures can drop below freezing. North winds are more frequent in winter. Rain is frequent from October to May, with an average accumulation of 17 to 22 inches per year. Nearly 16% of the population possess a bachelor’s degree or higher. The Sutter-Yuba district is considered rural because more than 75% of the total acreage in the district is devoted to agriculture, and rice accounts for nearly half of that agricultural acreage (Anon 2011). With 95% of historic wetlands lost in the Sacramento Valley, rice fields act as an alternate habitat for wildlife species and mosquitoes (Anon 2011).

The Sacramento-Yolo Mosquito and Vector Control District has about 1.7 million residents spread over about 2,000 square miles. The largest city is Sacramento with nearly 500,000 inhabitants spread over 97 square miles. The two counties are bordered by Colusa, Sutter, and Placer counties to the north, El Dorado and Amador counties to the east, San Joaquin and Solano counties to the south, and Napa County to the west (Figure 1). The district borders the Sacramento-San Joaquin Delta and the Suisan Bay. Summer temperatures are moderated by delta breezes coming from the San Francisco Bay through Suisan Bay and the Sacramento-San Joaquin Delta. The average temperature in the district is around 60 F. Over the past ten years the district has averaged about 15 inches of rain per year — less than normal because of several years of drought. More than one-third (34%) of the population possesses a bachelor’s degree or higher. In terms of agricultural production, rice is an important field crop in both counties with 23,000 acres harvested in Yolo County and 8,000 acres harvested in Sacramento County in 2015 (2015 Crop and Livestock Reports for Sacramento and Yolo Counties). Sacramento County had the state’s highest number of cases of West Nile virus in 2005, with 177 of the nearly 900 cases in California (Carney et al. 2008).

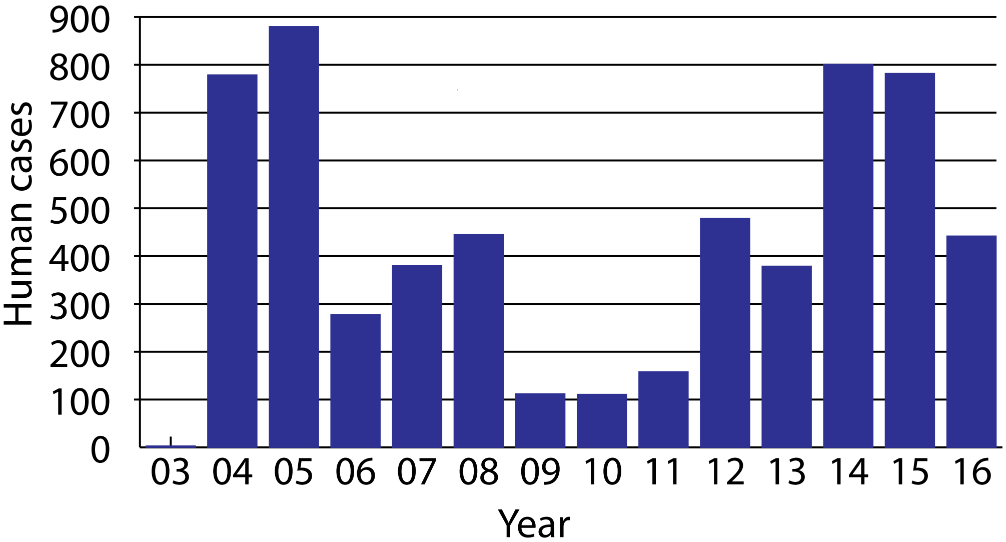


Figure 2. Human cases of West Nile virus in California

WEST NILE VIRUS IN THE WEST

West Nile virus is primarily a bird virus and mosquitoes spread the virus within bird populations and to nearby human populations. It is one of many flaviviruses known to cause disease in humans including Zika, yellow fever, dengue, and St. Louis encephalitis. Most cases of West Nile virus infection are asymptomatic. About 25% of the cases of West Nile virus infection develop into West Nile fever. In a smaller percentage of West Nile virus infections, the severe neuroinvasive disease develops resulting in encephalitis, meningitis, poliomyelitis or death. Risk factors for developing West Nile fever or neuroinvasive disease are poorly understood.

The spread of West Nile virus in the West following its introduction in the United States in 1999 resulted in several severe outbreaks with significant health implications (Reisen 2012). The outbreak of West Nile virus in Colorado in 2003 accounted for nearly 30% of the cases nationwide, of which more than 20% (621 out of 2,947) were the severe neuroinvasive form. The outbreaks in California in 2004 and 2005 accounted for nearly 30% of the cases nationwide, of which 37% (291/779) in 2004 and 35% (305/880) in 2005 were the severe neuroinvasive form. California has been among the states with the highest incidence and percentage (13%) of neuroinvasive disease caused by West Nile virus (Adams et al. 2013). Following the initial outbreaks in California in 2004 and 2005, the number of cases declined to a low of about 110 in 2009-10, but increased to 158 in 2011, and to over 800 cases in 2014 (Figure 2).

The medical costs associated with the virus outbreaks in California are staggering, and therefore prevention is the most cost effective way to deal with West Nile virus. For instance, in Sacramento County in 2005, the cost of the West Nile virus outbreak was nearly $3 million (Barber et al. 2010) or about $17,000 per case. The Sacramento-Yolo district calculated that the cost of the effort to control the northern house mosquito and the encephalitis mosquito was equal to the medical costs of 15 human cases. Therefore, preventing more than 15 cases results in a net cost savings and that cost savings continues to increase as more cases are prevented. The costs savings associated with prevention may be higher now compared to 2005 because medical costs have increased.

MOSQUITO VECTORS OF WEST NILE VIRUS IN CALIFORNIA

There are about 48 species of mosquitoes in four genera (*Aedes*, *Anopheles*, *Culex*, and *Culiseta)* in California. Of those, only the *Aedes* and *Culex* species are known to carry the West Nile virus in California, and we will focus on the *Culex* species because they seem to be the primary drivers of West Nile virus outbreaks in California. Within the *Culex* genus, the different species vary in where they live (urban and rural, Northern and Southern California) and the animals on which they tend to feed (birds and mammals) (Reisen 2012). In Northern California, the northern house mosquito and the encephalitis mosquito spread West Nile virus (Anon 2013). The northern house mosquito (*Cx. pipiens*) prefers to feed on birds in urban centers and is a problem in the greater Sacramento metropolitan area in Sacramento County. The encephalitis mosquito (*Cx. tarsalis*) prefers to feed on birds but will feed on mammals as well and inhabits rural areas, and tends to be more of a problem in Yolo, Sutter and Yuba counties. In Southern California, the southern house mosquito (*Cx. quinquefasciatus*) is one of the most common species collected (Krueger et al. 2015) and although a less efficient vector of West Nile virus compared to the encephalitis mosquito (Goddard et al. 2002), it is the vector driving West Nile virus outbreaks in Orange County (Kwan et al. 2010, Anon 2013).

The human populations and habitats within the counties, the different mosquito species, and aspects of the virus itself all affect how the three districts combat this threat.

Box 1. The PAMS approach to measuring the level of IPM adoption

The four practices included in PAMS are prevention, avoidance, monitoring, and suppression. Prevention is the practice of keeping mosquitoes out of an area (wetland, drainage ditch, house, pool, backyard). Changing the habitat to make it unsuitable for mosquito breeding is a good example of prevention. If mosquitoes are in an area, avoidance is used to prevent bites and transmission of disease, such as the use of window and door screens to prevent mosquitoes from entering homes. Measuring the size of the mosquito populations and the extent of virus activity in an area is considered monitoring. Examples include trapping adult mosquitoes to measure the size of the population and testing the mosquitoes for virus to measure virus activity. These trap numbers are compared to the threshold value to make a decision about suppression activities including the use of pesticides. Suppression is used to keep mosquito populations below threshold levels. Mosquito thresholds are based on the risk that they will cause disease in human populations. Examples include the use of biological (mosquito fish), microbial (*Bacillus* species), and chemical (pesticide) treatments.

CASE STUDY ANALYSIS

Integrated Pest Management used by California Mosquito and Vector Control Districts

Integrated pest management (IPM) is a best management practice that reduces the risks associated with pests and pest management (Philips et al. 2014). Best management practices used by the districts are often referred to as "integrated vector management" and "integrated mosquito management." In this section, we document how the best management practices used by the districts align with the elements of integrated pest management. Several metrics have been developed to measure IPM adoption based on the number of IPM tools used by a program, and we use these metrics to quantify IPM in these case studies. The IPM continuum describes different levels of IPM adoption ranging from low-level adoption and complete reliance on pesticides to high-level adoption where numerous tools are used to manage the pest population and pesticides are used only when the pest population has exceeded a treatment threshold (Philips et al. 2014). As we outline in this article, the mosquito and vector control districts are high-level adopters because their programs incorporate all of the elements of IPM including outreach and education, mosquito surveillance, treatment thresholds, biological and microbial control, physical and cultural control, and chemical control. Chemical treatments, especially pesticides applied by air over urban areas to manage adult mosquitoes, are used only when the surveillance data demonstrates that mosquito populations will exceed the treatment threshold and pose a significant risk to public health.

Another widely accepted system used to measure the level of IPM adoption was proposed by Harold Coble (2003), and is currently used by National Agricultural Statistics Service pest-management practice survey (USDA NASS). This system is referred to by the acronym PAMS (Box 1), where the letters in PAMS stand for prevention, avoidance, monitoring, and suppression. Measuring the district adoption of IPM using the PAMS approach similarly suggests high-level IPM adoption (Table 1).

Therefore, mosquito districts can be classified as high-level IPM adopters using either metric used to measure IPM adoption. The remainder of this report will highlight specific IPM tools or elements used by the three districts to protect people and the environment from harm caused by mosquitoes and the products used to control mosquitoes during the outbreaks of West Nile virus in California over the past decade.

Table 1. Examples of how the mosquito control districts use different elements of the PAMS approach

	Sacramento Yolo	Orange	Sutter-Yuba
Prevention			
Modification of agricultural and natural areas to reduce standing water	✓	✓	✓
Neighborhood notification campaigns to eliminate sources such as abandoned pools, standing water around container plants, underground storm drains	✓	✓	✓
Avoidance			
Outreach to promote the use of protective clothing and repellents, avoiding outside activities when mosquitos are active, and repairing or sealing routes of entry into houses	✓	✓	✓
Monitoring			
Tracking West Nile virus in human, bird, and mosquito populations	✓	✓	✓
Trapping adult mosquitoes	✓	✓	✓
Larval mosquito sampling with dip cups	✓	✓	✓
GIS mapping of human infections or mosquito and virus activity	✓	✓	✓
Dead bird surveillance program	✓	✓	✓
Suppression			
Biological control (mosquito fish) of larval mosquitoes	✓	✓	✓
Bio-rational or microbial control of larval mosquitoes	✓	✓	✓
Use of thresholds for making treatment decisions	✓	✓	✓
Ground applications of pesticides to control adult mosquitoes	✓	✓	✓
Aerial applications of pesticides to control adult mosquitoes	✓		✓

DISTRICT OUTREACH

In a typical year, the Orange County Mosquito and Vector Control District spends about 10% of its budget on outreach (Table 2). The district produces more than 150 media publications in multiple languages, prints more than 30,000 informational fliers in multiple languages and participates in more than 50 community-outreach events each year. In 2016, district employees visited more than 26,000 homes in a door-to-door campaign, and its web site had 65,000 visits. The district routinely provides information for stories in the Orange County Register that has a daily readership of about 116,000 (circulation statistics available at ocr.scng.com/media kits). The county has about 2.4 million residents over the age of 18 and likely to read newspapers or look up information about mosquitoes on the Internet. There's evidence that these outreach efforts are succeeding: a recent survey of 500 Orange County residents suggests that 50% of the population know of the vector control program and nearly 80% have contacted the district for help (Anon 2017).

Table 2. The amount and proportion of the total annual budget allotted to outreach efforts in three mosquito control districts in California

District	Total annual budget	Communications budget (and as a percentage of total annual budget)	Information source
Orange	$10.7 million	$1.1 million (10%)	2015 budget
Sacramento-Yolo	$11.0 million	$330,000 (3%)	2015 budget
Sutter-Yuba	$2.8 million	$40,000 (1.5%)	2015 budget

The Sacramento-Yolo County Mosquito and Vector Control District spends about 3% of its overall budget on outreach (Table 2). The district produces media publications and informational fliers, and participates in community outreach events. The Sacramento-Yolo District web site has about 53,000 visits per year. The district routinely provides information for stories in the Sacramento Bee that has a daily readership of about 280,000 readers. There are approximately 1.1 million inhabitants over the age of 18 years old in the Sacramento-Yolo Mosquito Control District area and likely to read newspapers or look up information about mosquitoes on the web.

The Sutter-Yuba County Mosquito and Vector Control District spends about $40,000 on outreach every year, and that accounts for about 1.5% of its annual budget (Table 2). The district produces mailers, brochures and pod casts, and maintains a website. The district participates in community-outreach events and provides information for stories in the Sacramento Bee. The Sacramento Bee serves the entire Sacramento Valley including Sutter and Yuba counties.

District outreach through printed and electronic media and in-person participation at community events successfully prevents mosquito bites and transmission of disease by raising awareness of the importance of preventing mosquitoes from entering the home through the use of screens, avoiding times of day when mosquitoes are active, wearing protective clothing, using mosquito repellents, and draining standing water around homes to limit breeding sites (Center for Disease Control).

Boy Scouts visiting the Orange County Mosquito and Vector Control District office

Supplying information for newspaper articles is critical for collecting crowdsourced information on virus activity in wild bird populations through the "dead bird surveillance" program. Because the West Nile virus exists as a disease that regularly affects birds, finding dead birds and submitting them for analysis is crucial for monitoring the activity and location of hot spots and predicting the risk of virus spread to humans. There is clear correlation between news releases and the number of reported dead birds (Foss and Padgett 2016), so district outreach efforts affect public behavior — by increasing submissions of dead birds — which in turn leads to better monitoring of virus activity in bird populations.

The news media remains a critical partner for the districts in their outreach efforts. News stories generate interest in the subject of mosquitoes and mosquito-borne illnesses leading to successful prevention efforts and a successful dead bird surveillance program. Unfortunately, media attention does not closely track outbreaks. Newspaper coverage increased during the early outbreaks in 2004 and 2005, but has continued to decrease in recent years despite the rise in West Nile cases (Figure 3). Many possible explanations for the decrease in news coverage of West Nile virus exist. It is possible that a decades-old public health issue is no longer newsworthy when more recent public health concerns exist, such as Zika. It is also possible that staff changes, changing news focus, and decreasing space in newspapers has led to the decline in news coverage of West Nile virus. Regardless of the reason for the decline, the trend suggests that it may be difficult to maintain a high level of public interest through traditional news outlets over long periods of time. Other outreach outlets are being explored by the districts, such as social media platforms. However, there are no data showing social media efforts can sustain interest in public health issues such as West Nile virus over long periods of time.

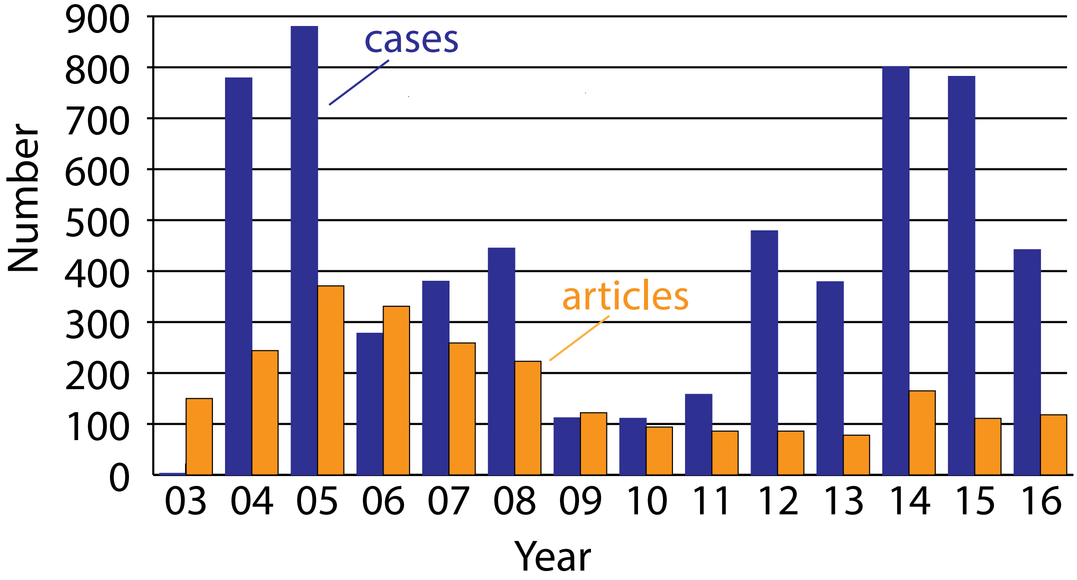


Figure 3. Number of human cases in California (blue bars) and the number of newspaper articles about mosquitoes and West Nile virus in the Sacramento Bee and Orange County Register (orange bars). Newspaper articles about mosquitoes and West Nile virus were searched through NewsBank (infoweb.newsbank.com). The Sacramento Bee serves as a primary news source for the counties of Sacramento, Yolo, Sutter and Yuba. The Orange County Register serves as a primary news source for Orange County.

SURVEILLANCE

Surveillance includes monitoring mosquito abundance, monitoring virus activity in mosquito and vertebrate hosts, and mapping. Surveillance is important because more mosquitoes and higher virus activity means a higher risk of disease outbreak (Godsey et al. 2012). But the precise relationship between surveillance data and risk of human disease remains an area of active debate and scientific investigation. This relationship between surveillance data and disease risk is important because treatment thresholds — triggers for suppression activities such as pesticide applications — are built on it.

Recent advances have greatly improved the precision of the surveillance data. Sampling strategies that provide high degrees of certainty, crowdsourcing the surveillance of dead birds, and increased availability of geographic information system (GIS) tools have significantly improved the ability of districts to assess the risk for human disease and pinpoint those areas where the risk is highest (Nguyen et al. 2015). Accurate prediction of the area requiring treatment leads to reduced risk of disease and reduced exposure to pesticides. Disease risk is reduced because an accurate strike against a mosquito population effectively eliminates most or all of the mosquitoes, and pesticide exposure is reduced because only the specific area of risk is treated.

Mosquito control districts track adult mosquito populations using adult mosquito traps and the different traps vary in their effectiveness at catching different mosquito species. However, it is generally accepted that increasing trap density, the number of traps per unit area, is the best way to increase the precision of the surveillance data. Increased trap density comes at a cost and those districts with smaller budgets because of lower population densities and lower tax bases are not in a position to easily increase trap density. The Orange County district runs between 150 to 300 traps per week [0.2 to 0.4 traps per square mile (150 to 300 traps divided by 791 square miles)]. The Sacramento-Yolo district runs about 80 traps within the city of Sacramento, leading to a trapping density of 0.8 traps per square mile (80 traps divided by 97 square miles). The Sutter-Yuba district runs about 53 traps for a trapping density of 0.07 traps per square mile (53 traps divided by 706 square miles). Healy and colleagues (2015) demonstrated that more precise estimates of West Nile virus infection prevalence in mosquito populations could be attained at a trap density of 0.3 traps per square mile. Therefore, the trapping densities in Sacramento City and Orange County are high enough to precisely delineate areas of West Nile virus risk. And, as we will show later, the increased precision and certainty leads to lower pesticide exposure because areas targeted for adult mosquito suppression using pesticides are smaller.

Table 3. Number of public health articles in PubMed (www.ncbi.nlm.nih.gov) citing the use of QGIS (open source GIS software) and ESRI ArcView from 2014 to present

Date Range	Number of articles in PubMed citing the use of QGIS (and as a percentage change)	Number of articles in PubMed citing the use of ESRI ArcView (and as a percentage change)
2016 to present	9 (350)	90 (-55)
2014 to 2016	2	200

The dead bird surveillance program employs the help of citizens to report dead birds sightings. This crowdsourcing effort was initiated in 2000 and has been essential in detecting and monitoring virus activity (Anderson et al. 2010). In 2004 and 2005, more than 90,000 reports were submitted through the program (Anderson et al. 2010). In 2015, nearly 11,000 reports were submitted (Foss and Padgett 2016). Healy and colleagues (2015) estimate that the dead bird surveillance program is one of the most cost-effective ways to monitor West Nile virus activity. The program has provided significantly more data leading to improved precision of mosquito suppression efforts. There is a clear correlation between news releases and the number of reported dead birds (Foss and Padgett 2016), and therefore the success of the dead bird surveillance program is dependent, in part, upon media coverage.

Open source geographic information system (GIS) software and free imagery have improved the usability of mapping tools making them more accessible to public health organizations including mosquito control districts. Open source GIS software has been available for more than a decade (Steiniger and Hunter 2012), and the quality of these programs has increased substantially in the past several years (Dempsey 2016, Altaweel 2017). The large number of customizations has led to increased usage, especially in the public health arena (Table 3). The use of QGIS in the past 2 years has increased dramatically compared to the two years prior to 2016 (Table 3), a trend that was noted at the recent National Extension Technology Conference (NETC 2016) in Kissimmee, Florida. Industry standards such as ESRI ArcView cost several thousand dollars and require significant technical expertise. QGIS, and other open source software, are free and do not require significant technical expertise to operate (Feygin 2011). Landsat images that used to cost hundreds to thousands of dollars are now freely available through the U.S. Geological Survey. The accessibility of these tools has resulted in the mapping of areas based on risk — identified by indicators such as dead bird surveillance, mosquito trapping and human cases — that in turn have led to better precision in deploying mosquito suppression tactics.

Managing Mosquito Larvae

The two mosquito life stages, larva and adult, targeted for suppression are discussed separately because the goals and strategies for managing them differ. Management of mosquito larvae aims to prevent the emergence of adult mosquitoes, the stage injurious to people. Larval mosquito management includes habitat modification, mosquito fish, bio-rational products, and chemical treatments. The different management options fit together into the different programs used by the three districts — like pieces of a puzzle. Although the management options available for larval suppression are relatively benign to humans and the environment, their drawbacks and strengths define how they can be used most effectively in an overall integrated approach.

Modifying habitats to increase flows and reduce stagnant water can effectively suppress mosquito larvae by limiting the availability of breeding sites. But habitat modification tools and restrictions on their use differ between rural and urban communities. In predominantly rural districts, larval mosquito management efforts may occur in natural and conservation areas and rice fields, and the mosquito control districts align their goals of reducing mosquito populations with the habitat-preservation goals of wetlands managers (including the National Marine Fisheries Service, Department of Fish and Wildlife, and Army Corps of Engineers) seeking to preserve critical habitats, and the production goals of agricultural producers (Shanahan 2013). Wildlife managers and mosquito control districts work together to develop environmental assessments and management plans that satisfy the goals of both groups. In urban communities, habitat modification might be the removal of debris in a culvert to decrease pooling water, or draining of abandoned or unused swimming pools. Districts have broad authority to eliminate breeding sites on private land, but must use court-approved methods and due process to gain entry to privately owned property.

Dipper sampling for larval mosquitoes (Orange County Mosquito and Vector Control District)

Areawide pest management has proven to be effective in agriculture (Elliott et al. 2008). For instance, the management of Lygus bug, beet leafhopper and whiteflies in the safflower, cotton, tomato rotation in Fresno County, California is achieved by areawide management (Anon 2016c). The Sutter-Yuba district currently employs a highly effective areawide management strategy as well. By quickly flooding wildlife habitats on a landscape scale, an entire generation of mosquitoes hatches synchronously. The district can then time its larval and adult treatments to eliminate an entire generation of mosquitoes. Areawide management in metropolitan areas such as Sacramento City and Orange County may be more difficult because of the complexity of the habitat and the number of stakeholders that would need to be engaged.

Biological controls are widely used by mosquito control districts, and districts maintain active programs in rearing and distributing different species of mosquito fish including western mosquitofish or *Gambusia affinis*, guppies or *Poecilia reticulata*, and threespined stickleback or *Gasterosteus aculeatus.* These fish-rearing programs are well established and releasing fish effectively eliminates larval mosquito populations. But western mosquitofish can be invasive and appropriate precautions are needed to prevent negative impacts on sensitive wetland habitats and fish species (Schleier et al. 2008).

Districts track larval mosquitoes populations in water sources using dip-cup samples to inform the decision to treat a water source with bio-rational or chemical products. The dip-cup is a one-pint cup attached to the end of a dowel and water is dipped or sampled for the presence of mosquitoes. Technicians in the districts check new and known habitats for mosquitoes at regular intervals that may depend on how remote or accessible the site is. The decision to treat larval mosquito populations is based on the treatment threshold. The threshold currently used by the three districts for *Culex* species is more than one mosquito larva in 20 dip-cup samples (Boyce 2005, Anon 2010). But the decision to treat is not solely based on mosquito abundance and also takes into account the presence of sensitive non-target and biological control organisms (Boyce 2005, Anon 2010). The larval thresholds used to make treatment decisions are revisited frequently and refined to incorporate new information.

Bio-rational suppression products are based on naturally occurring microbes. These microbial controls include a variety of products based on *Bacillus thuringiensis isrealiensis*, *B. sphaericus*, and *Saccharopolyspora spinosa.* The products based the *Bacillus* bacteria contain dead bacteria or live spores that can remain effective in the water for several weeks. The products based on *S. spinosa* contain spinosins — chemicals that are lethal to mosquito larvae and kill quickly. We calculated the risks of the microbial products to environmental and human health using the ipmPRiME risk assessment tool (Guzy et al. 2014). The ipmPRiME tool calculates the likelihood that a product will impact an organism using the species sensitivity to that material and the level of pesticide exposure — more exposure and higher sensitivity leads to a higher risk of moderate to severe impact. The ipmPRiME tool estimates environmental risks — risks posed to birds, small mammals, fish, earthworms, crustaceans and algae — and human health risks. The risk assessment tool indicated that the bio-rational or microbial products used by the districts all pose low environmental and human health risks (Table 4).

Chemical treatments have an important fit in larval mosquito management programs. The chemical treatments include surface agents and insect growth regulators. Surface agents, such as refined mineral oils and monomolecular films act by suffocating the mosquito larvae and work well in stagnant water with little to no wind. The insect growth regulators such as S-methoprene and

Table 4. Risks of acute and chronic toxicity for invertebrates and vertebrates (including humans) calculated using the ipmPRiME risk assessment tool

Product name	Chemical	EPA number	Risk to vertebrates	Risk to invertebrates
Vectobac 12AS	*Bacillus thuringiensis*	73049-38	Low	Low
Teknar HP-D	*Bacillus thuringiensis*	73049-404	Low	Low
Vectolex WDG	*Bacillus sphaericus*	73049-57	Low	Low
Dimilin 25 W	diflubenzuron	400-465	Low	Low
Natular 2 EC	spinosad	8329-82	Low	Low
Altosid liquid larval concentrate	S-methoprene	2724-446	Low	Low
Altosid briquette	S-methoprene	2724-375	Low	Low

Shown here is the risk that a material will exceed the "no observed adverse effect" level set by EPA. For this analysis we used the highest labeled rate for the specific use of each material. The materials listed were used in at least one of the five California counties in this report from 2004-2015 (California Pesticide Use Reporting database). Risk is summarized for each of the following vertebrate and invertebrate categories. The vertebrate category summarizes data for birds (chance of bird kill or reduced reproduction), small mammals (chance of population declines), fish (chance of population declines and reduced reproduction), and humans (inhalation risk to bystanders). The invertebrate category summarizes data for earthworms (chance of kill), aquatic crustaceans (chance of population declines), and algae (chance of population declines). Risks were placed into categories of high (probability greater than 50%), moderate (probability between 10 and 50%), and low (less than 10%).

Raising mosquito fish in the Orange County Mosquito and Vector Control District facility

pyriproxyfen function by interfering with the normal development of the larvae because they mimic juvenile hormone. The Altosid briquettes based on S-methoprene remain effective in the water for more than a month — very useful for remote locations that are infrequently visited. Diflubenzuron interferes with normal development of the insect cuticle by disrupting chitin synthesis. The insect growth regulators pose little risk to human and environmental health (Table 4). The risk of surface agents to non-target organisms could not be tested in the ipmPRiME tool, but these are relatively nonspecific in how they kill mosquitoes and therefore could affect other aquatic invertebrates as well.

Managing Mosquito Adults

Mosquito districts initiate adult mosquito suppression when the threat to human health exceeds a threshold level. The three districts use similar thresholds based on mosquito trap captures, the prevalence of virus-infected mosquitoes, the prevalence of virus in the wild bird populations or sentinel chicken flocks, and the presence of human cases (Boyce 2005, Anon 2010).

Treatment thresholds track the human health risk posed by mosquitoes, and therefore, treatment intensity — measured by the number of acres treated — should increase with increase risk. This trend was observed from 2004 to 2007 in both rural and urban areas (Figure 4). However, when the risk of disease again increased in 2012 to 2015, treatment intensity tracked risk in rural areas, but not for aerial applications over the urban areas of Sacramento (Figure 4). The Sacramento-Yolo district was able to reduce treatment intensity in urban settings by adjusting its sampling strategy. More importantly, Sacramento did not experience a West Nile virus outbreak in the human population despite the lower treatment intensity. By increasing the trapping density and by using mapping tools, the district precisely delineated areas of risk and pinpointed its treatment. The district minimized the risks to human health by effectively reducing the number of host-seeking adult mosquitoes in the area of concern and minimized the environmental and human exposure and economic costs associated with the pesticide application by limiting the treatment area (Carney et al. 2008, Macedo et al. 2010).

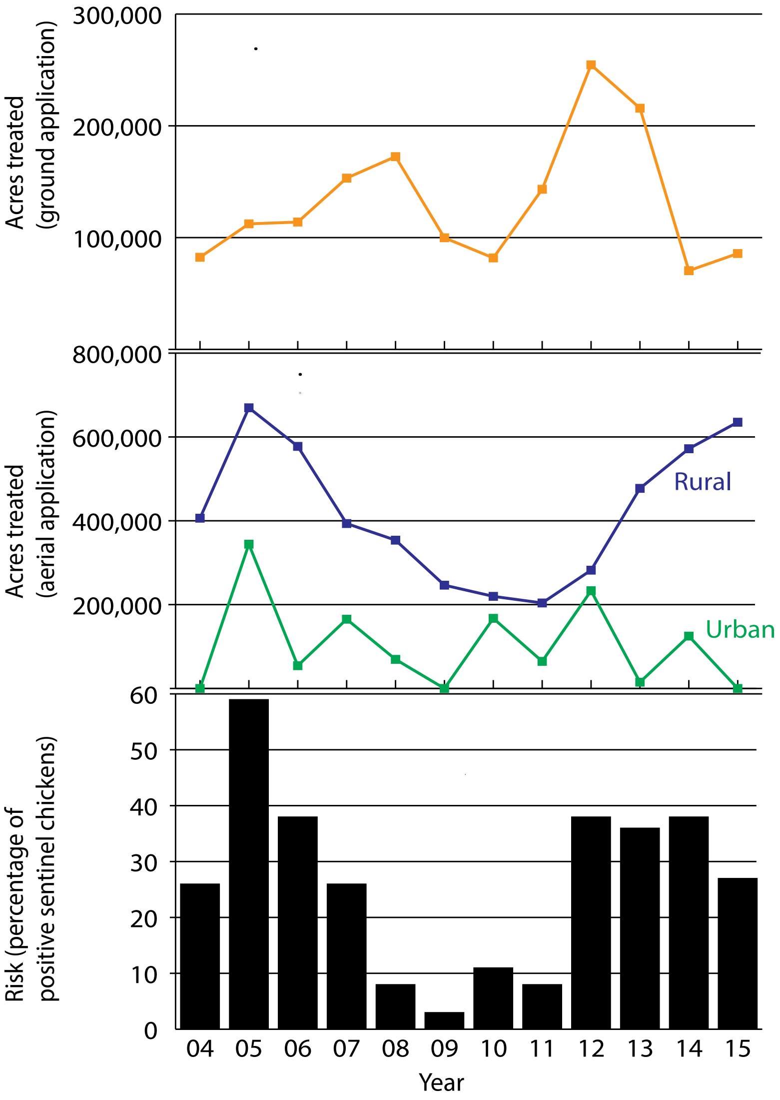


Figure 4. Risk (indicated by the proportion of the sentinel chicken population seropositive for West Nile virus) and acres treated with adulticides (by ground and by air) in the Sacramento-Yolo Mosquito and Vector Control District. Ground and rural aerial sprays have tracked risk, whereas the number of urban acres treated has been minimized despite increasing risk from 2012 to 2015. Data from the Sacramento-Yolo Mosquito and Vector Control District database on pesticide use in the counties.

The same treatment threshold is used in rural areas and this is clearly demonstrated by plotting risk and treatment intensity in the rural areas of the Sacramento-Yolo district (Figure 4). As the human health risk posed by mosquitoes increases, so do the number of acres treated (Figure 4). The same trend is true for the Sutter-Yuba district (data not shown). But rural districts restrict treatments to relatively unpopulated areas and instead use border sprays around towns to reduce the risk to human health from pesticide applications. The border spray technique is successful in northern California rural communities because of the species of mosquito and its behavior. The encephalitis mosquito resides in the agricultural fields surrounding smaller urban centers and moves from agricultural fields into urban centers seeking mammalian hosts. Border treatments around urban centers effectively reduce the bridge for the virus and minimize human exposure to pesticides used to control adult mosquitoes.

The public tolerance to risk posed by mosquitoes appears to vary with their perception of the severity of the disease the mosquitoes carry. In most cases, there are no symptoms of West Nile virus infection, or at most a fever. The more severe and life-threatening neuroinvasive form occurs at a relatively low rate in California when averaged across years (13%). Therefore, the perceived risk of West Nile virus is relatively low, and this leads to opposition to the use of pesticides to control adult mosquitoes. In Orange County, the majority of people who contacted the hotline after the announcement that the district would begin aerial treatment in 2015 were opposed to the action. There are also websites specific to Orange County that are opposed to the use of pesticides to control mosquitoes (such as nontoxicirvine.org). Although these anecdotal data suggest opposition to treatment with pesticides, they do not indicate the proportion of the population in Orange County that is opposed to aerial spraying. The Orange County Mosquito and Vector Control District did not conduct an aerial spray in 2015 because of permitting issues. It is currently able to perform aerial sprays, but requires a specific vote by its 35-member Board of Trustees to authorize every aerial application.

The human health risks and environmental risks posed by the pesticides used to manage adult mosquitoes are low (Peterson et al 2006, Weston et al. 2006, Davis et al. 2007, Antwi and Peterson 2009, Macedo et al. 2010, Peterson 2010, Preftakes et al. 2011, Geraghty et al. 2013). To further reduce the risks associated with pesticide application, mitigation strategies are used to prevent exposure of non-target organisms (Davis et al. 2007). These mitigation strategies include spraying at times of day when mosquitoes are active and non-target species are inactive, communication with stakeholders and others, and border spraying around towns in rural areas. The impact on non-target organisms such as honeybees can be high if mitigation strategies are not employed (Ginsberg et al. 2017).

CONTINUING NEEDS

Effective control efforts against yellow fever mosquito, *Aedes aegypti*, in the Americas may have led to complacency and abandonment of mosquito control programs, and this complacency may have led to a resurgence of mosquito populations and widespread disease transmission, including West Nile virus and more recently Zika and chikungunya (Anon 2016a). It has been proposed that the recent outbreak of dengue fever in Hawaii resulted from the economic downturn in 2008-2009 and the removal of funding from the mosquito control program (Anon 2016b). Continued vigilance of disease vectors is crucial to maintaining human health, and IPM will continue to be one of the best ways to combat these threats while also minimizing environmental impacts and economic costs.

The correlation between reports to the dead bird surveillance program and media attention measured by the number of articles in newspapers and television demonstrates the importance of local media as a partner in protecting the general public from risks such as mosquitoes and West Nile virus. However, maintaining media interest in mosquitoes during non-outbreak years can be difficult, and finding other venues that will help to maintain public interest in the risks posed by mosquitoes will be important. The districts are active on social media platforms and an analysis of the data will help understand the impact of these efforts. For instance, can social media posts sustain interest in the dead bird surveillance program in the same way as the print media did?

The stories and interest in West Nile virus in the news media may have diminished because of newer vector-borne diseases with more significant human health impacts, such as Zika virus. And certainly the loss of media interest in West Nile virus could be viewed as negative because the campaign to promote behaviors that limit exposure to mosquitoes, and crowdsource efforts to monitor West Nile virus rely on news media to maintain awareness. But new diseases such as Zika could raise general awareness of mosquitoes and the diseases they vector and thereby benefit district efforts to control all mosquito species, including those that transmit West Nile virus.

Pesticides, both pyrethroids and organophosphates, used for adult mosquito control were developed in part by the U.S. Department of Defense to protect troops from mosquito-borne illness in theaters of war. But these pesticides were developed more than 50 years ago and have human health concerns related to their use. Because these pesticide groups have been in use for a long time and many generations of mosquitoes have been exposed to them, there are also concerns about mosquito resistance. Therefore, new low-risk, narrow-spectrum pesticides are needed for control of adult mosquitoes. Currently, legislative and research efforts are under way to develop new materials that can be used to control adult mosquitoes. It is crucial that new control materials are available because public opinion, regulatory restrictions, and the development of insecticide resistance in mosquito populations will make the use of organophosphates and pyrethroids more difficult in the future.

Interest in biopesticides or bio-rational products has been strong over the past several decades and new products in vector control may be available relatively soon. For example, *Wolbachia pipientis* is a rickettsial bacterium that naturally infects insects, and in mosquitoes, it has been shown to reduce the spread of disease (Walker et al. 2011, Caragata et al. 2016). In the United States, the *Wolbachia* bacterium is currently being tested against the yellow fever mosquito (*Aedes aegypti*) in California (Dobson 2015, Anon 2016d) and registration is under way for a product to control Asian tiger mosquito (*Ae. albopictus*) in the U.S. (Waltz 2016). Because the current work is focused on the yellow fever mosquito and Asian tiger mosquito, it might not immediately help in the fight against West Nile virus. But success of a biopesticide against yellow fever mosquito may spur additional research efforts against other mosquito targets and the diseases they carry.

Education about the concept of risk, associated with both pesticide use and mosquitoes, is necessary to assure that the risks and benefits associated with vector control are broadly understood. The public perception of the risk of West Nile virus appears to be low, but the data support a higher level of risk both in terms of the proportion of neuroinvasive cases during outbreak years and in terms of the medical costs associated with the disease. The annual rate of neuroinvasive disease in California is 13%, but rises to nearly 40% in outbreak years, and the medical costs associated with the outbreak in Sacramento City was nearly $3 million. The public perception of the risk associated with pesticide use is relatively high (compared to the perceived risk of disease), and yet the scientific evidence does not indicate significant risk posed by the pesticides used for adult mosquito control. The scientific evidence clearly demonstrates the risk to human health posed by mosquitoes is higher than the risk posed by pesticides used to control the mosquitoes (Peterson et al 2006, Peterson 2010). People in the United States have become increasingly concerned about the effects of pesticides (Pimentel and Acquay 1992), and the assurances provided by regulatory agencies that pesticides pose little risk to public health have been undermined by data showing pesticide contamination in soil, water and air, and data that link these materials to a wide range of poor human-health outcomes (Harrison 2014).

Summary

Integrated pest management mitigates the risks to human health and the environment associated with pests and their management in the most economical way possible. The core of IPM is evidence-based decision making. As defined above, and from all of the evidence presented here, it is clear that these three mosquito control districts employ high-level IPM. And in so doing, the districts are achieving their goals of protecting the public from the risk of mosquito-borne illness, protecting people and the environment through the judicious use of pesticides, and ensuring the public trust by achieving these goals in the most economical way possible. However, the districts continue to face new challenges including new or resurgent diseases and mosquito species, and rapidly increasing human populations, while working under increasingly restrictive regulations and shrinking budgets.

Technology will undoubtedly solve some of the problems faced by the districts. New control strategies including the mosquito-infecting bacterium, *Wolbachia*; remotely controlled or completely autonomous vehicles for detecting and controlling mosquito populations; and low-risk pesticides for adult and larval control are not far in the future. These technologies should provide more efficient control at a lower cost. In addition, districts will have additional cost savings as newer technologies become less expensive as already demonstrated by the decreased cost of using GIS tools.

In this case study we have documented the many management tools used by the districts and tried to show how the districts fit these tools together into an overall integrated pest management program that aligns with the goals of the communities they serve. The districts use outreach, surveillance, areawide management, habitat and breeding site management, biological and bio-rational controls, treatment thresholds, and pesticides. In addition, we have highlighted how the districts continue to incorporate new science and information, management techniques, and technologies in their integrated pest management programs, and how these advances have reduced costs and improved efficiency, and improved the ability of the mosquito abatement districts to protect people and the environment from risks posed by mosquitoes and the mosquito management tools.

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