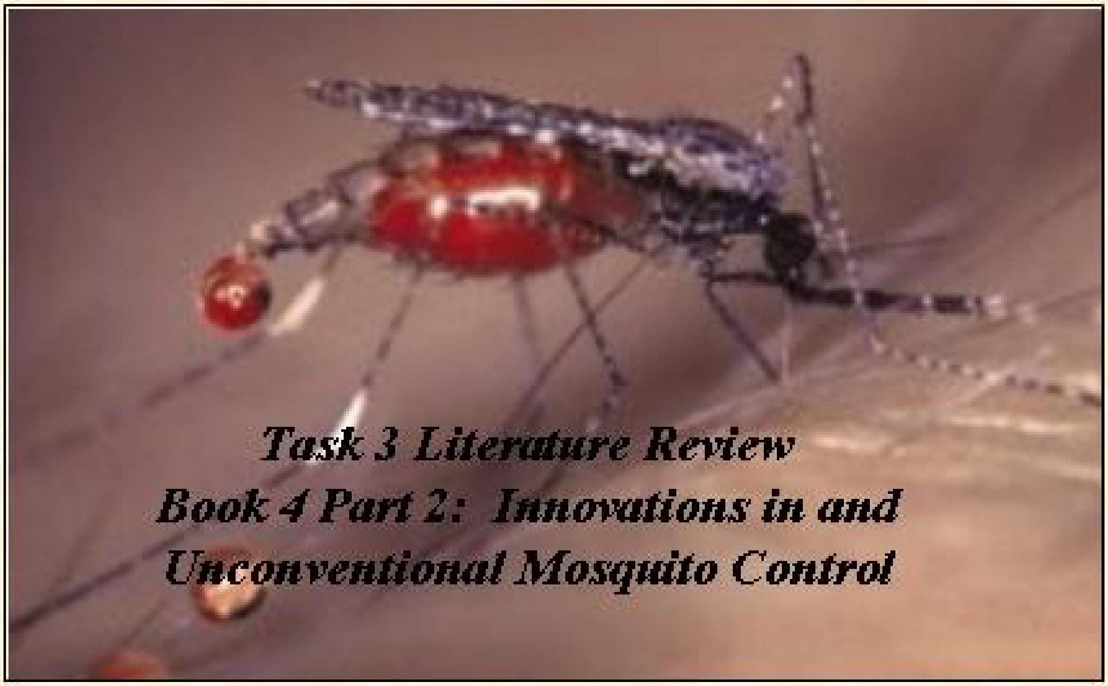
Suffolk County Vector Control & Wetlands Management Long Term Plan & Environmental Impact Statement



Task 3 Literature Review
Book 4 Part 2: Innovations in and Unconventional Mosquito Control

Prepared for:

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Suffolk County Department of Health Services
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SUFFOLK COUNTY VECTOR CONTROL AND WETLANDS MANAGEMENT LONG - TERM PLAN AND ENVIRONMENTAL IMPACT STATEMENT

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AGDISP	Ag Display
AMCA	American Mosquito Control Association
BSL	Biosafety Level
Bs	*Bacillus sphaericus*
Bt	*Bacillus thuringiensis*
Bti	*Bacillus thuringiensis israelensis*
CDC	Centers for Disease Control and Prevention
CO_2	Carbon dioxide
DDT	1,1,1-trichloro-2,2-bis(p-chlorophenyl)ethane
DEET	N, N-Diethyl-m-Toluamide
EEE	Eastern Equine Encephalitis
EIA	Enzyme Immunoassay
ELISA	Enzyme Linked Immunosorbent Assay
FIFRA	Federal Insecticide, Fungicide, and Rodenticide Act
GIS	Geographical Information System
GPS	Global Positioning System
HCMC	Harris County Mosquito Control
IGRs	Insect Growth Regulators
IMM	Integrated Mosquito Management
IPM	Integrated Pest Management
SLE	St. Louis Encephalitis
MODIS	Moderate Resolution Imaging Spectroradiometer
MSF	Monomolecular Surface Films
NASA	National Aeronautics and Space Administration
NOAA	National Oceanic and Atmospheric Administration
NYSDOH	New York State Department of Health
PBO	Piperonyl butoxide
PCR	Polymerase Chain Reaction
RAMP	Rapid Analyte Measurement Platform
SLE	St. Louis Encephalitis
STAB	Stand Alone on Board
TPS	Tadpole Shrimp
ULV	Ultra-low Volume
USDA	US Department of Agriculture
USEPA	US Environmental Protection Agency
VDCI	Vector Disease Control Incorporated
WHO	World Health Organization
WNV	West Nile Virus

Executive Summary

The standard for mosquito management is a hierarchy established under the concept of Integrated Mosquito Management. This calls for mosquito control through:

- Surveillance
- Source Reduction
- Larval control
- Adult control

Public education is another essential component of the program, used to establish the purpose for, and to reinforce the activities associated with, the four elements listed above.

Innovations in each of these areas are continuously developed by private industry and mosquito control districts. Not all proposed innovations in mosquito control are successful, however, as such, proposals to adopt new methods in vector control need to be carefully evaluated.

Source reduction, traps, and repellents

Aerial mapping services are now being commercially offered to identify mosquito breeding sources in inaccessible city/county lands, thus, leading to possible source reduction. Demonstrated alternatives to ditching continue to be propagated throughout the country. As for traps and repellents, newer products in this area include garlic oil repellents and propane-based traps. Limited testing has shown some efficacy for these products under certain conditions. However, not all product claims have been verified and the ability of these products to control mosquitoes, other than for localized areas with low mosquito densities, has not been demonstrated. For example, propane based traps collect mosquitoes, but not necessarily in numbers large enough to be considered control.

Genetic Control

Use of genetic controls on mosquito populations, such as the release of sterile males to occupy potential breeding females, has not been especially successful in the past, but it continues to engage the interest of researchers

Transgenic Control

Research is being conducted to determine if mosquitoes can be manipulated so that they will no longer be fit as vectors. This generally means changing the underlying genetic code of the organisms so that the bacteria or virus responsible for human disease can no longer survive in the mosquito, and, therefore, cannot be transmitted through mosquito bites. Additionally, mosquito parasites may have their genes manipulated to increase their virulence. This could make them more effective in reducing mosquito populations. Some very current research has focused on a parasite that infects *Culex* mosquitoes, which has important implications regarding West Nile Virus. There are some potentially serious environmental implications to this work, and, to date, it has not moved from the laboratory to the outside world.

Portable resting stations and traps for surveillance

Portable resting stations and CDC light traps are receiving increased attention, as these can be used to determine mosquito numbers in habitats close to homes and do not have the operational problems that can occur when other, more permanent, devices are utilized.

Use of birds in surveillance

Because West Nile virus (WNV) and some other mosquito-borne arboviruses have a link to avian populations, there is increased interest in monitoring bird populations. Dead bird testing is useful in West Nile surveillance, as it may indicate the presence of virus in an area. Capturing wild birds for WNV, or other virus monitoring, has some major limitations and difficulties. Sentinel flocks hold more promise as a monitoring means, although the time required for serum conversion may be a problem for some species, such as chickens.

Virus detection

Technology advances for virus detection include traditional viral isolation, antigen detection, and serological techniques, as well as newer molecular biology techniques. Virus isolation and identification techniques require a high level of biosafety containment. Other molecular biology techniques, such as ELISA and PCR, only require standard laboratory facilities to conduct. Some of the "dip-stick" technologies (EIA) provide quick and simple virus detection and can be performed virtually anywhere. These quick-test advances allow for rapid responses to potential disease situations.

Computer advances in surveillance

Geographic information system (GIS) mapping holds immense promise in data analysis for surveillance purposes. Some research also indicates that remote sensing data may be useful in predicting disease outbreaks by allowing for predictions of mosquito breeding.

Larvicidal products

Traditional chemical mosquito larvicides remain available for vector control usage. However, the bacterial products *Bacillus thuringiensis var israelensis* (Bti) and *Bacillus sphaericus* (Bs) are more widely used. Also, newer, timed-release products have been released, despite some jurisdictions having reservations regarding the potential for resistance development, due to long exposures with some of the formulations. New technologies continue to develop for treating storm drains for *Culex* mosquitoes, vectors of West Nile virus, such as specially shaped methoprene briquets to fit through storm drain grates and methoprene pellet applicators. Monomolecular films appear to have few environmental problems, but may not be appropriate for use in all environments. A new insect growth regulator, Novaluron, shows promise as an addition, or alternative, to other products. More testing and government approvals are required before it is useful, however. Research regarding the properties of essential oils, especially as larvicides, continue in Asia, but has not reached the stage of developing practical applications. Ultrasonic repellers for mosquitoes are ineffective. However, devices using sound waves to kill mosquito larvae appear to work, but are expensive, have operational difficulties, and work over limited ranges. Most biological controls, other than fish, show limited effectiveness and/or operational problems, as with parasites and copepods.

Adulticidal products

Effective insecticides continue to be available for adult mosquito control. The most commonly used products are pyrethroids, which are generally considered to be environmentally friendly and to have low mammalian toxicity. Several pyrethroids are available, or are now being formulated, as water-based solutions. Because of the high development costs and relatively small market for mosquito control, few new pesticides are being developed by industry for adult mosquito control. Widely used adulticides are limited to two organophosphates, malathion and naled; natural pyrethrin; and three synthetic pyrethroids, permethrin, resmethrin, and sumithrin. Because of fiscal, regulatory, and efficacy issues, the same compound may be applied in an area for prolonged periods of time. This causes concerns in light of potential development of insecticide resistance. GIS products and dispersion modeling are being touted as means of better understanding and controlling chemical applications. A general consensus has been reached that control of adult mosquitoes by predators is largely ineffective.

Program Innovations

Public scrutiny of vector control activities with the spread of WNV has increased interest in various aspects of mosquito control program administration. The notion of absolute triggers for mosquito control activities is being discussed. However, no clear consensus regarding the value of such controls, or what level of adult mosquito density is of concern, has been reached. There are clear indications that quantitative measures of program effectiveness, such as reductions in mosquitoes following treatment, either in situ or as a treatment-control process, are being more widely adopted, as well as quality assurance programs to limit misuse or misapplication of pesticides.

It is important to recognize that continuing education for the managers of the mosquito control programs is key for the evaluation of potential innovations to any local program. Worthwhile endeavors include annual conferences hosted by the American Mosquito Control Association, and the Society of Vector Ecologists, and the more local, but important meetings hosted each year by the New Jersey Mosquito Control Association and the Northeastern Mosquito Control Association. New Jersey, in addition, has held monthly meetings of mosquito control managers for over 75 years. At these meetings information is shared and speakers are invited, in order to provide the best opportunities for the local program managers to learn of advances and/or ineffective programs in the field. Absent professional education, program managers will have to rely on appraisals of the information provided by sales people and product vendors, which, as is discussed in this report, generally lacks peer review and other independent scrutiny, except for those products, such as pesticides, that may require regulatory approvals or permits.

1. Introduction

Mosquito control programs are experiencing changes driven by public pesticide fears, environmental concerns, and litigation. The Integrated Pest Management (IPM), Integrated Mosquito Management (IMM) when specifically designed for mosquito control, practices utilized by most modern mosquito control programs emphasize monitoring, via surveillance, early intervention, and the use of smaller quantities of less toxic pesticides (CDC, 2001; ASTHO, 2004). New and innovative techniques are being developed for mosquito control including acoustic devices to kill larvae, new "non-toxic" pesticides, propane-operated mosquito traps, and more. Modern mosquito control efforts generally focus on breeding source reduction, larviciding, and only using adulticides as a last recourse. Public education outreach programs are an integral and necessary part of IMM. They encourage people to proactively reduce mosquito-borne disease risks around the home. Furthermore, they help people understand why mosquito control managers choose particular control options to address potential mosquito problems.

Innovations in mosquito control have been adopted by specific programs at different rates, and to different degrees. Innovations should be understood in the context of some standard techniques. Therefore, this report contains brief descriptions of many widely used, standard approaches to mosquito control. Some of these are not commonly used on Long Island, however. The bulk of this section discusses new products and techniques available to mosquito control agencies for regional control efforts, or marketed to individuals for smaller scale efforts. The role of natural or augmented predation as a means of controlling mosquito populations is also addressed.

Nearly all of the new products discussed here are considered minimum risk compounds by the US Environmental Protection Agency (USEPA) and, therefore, do not require federal registration under the Federal Insecticide, Fungicide, and Rodenticide Act (FIFRA). Furthermore, in most states, some of these newer products are not considered pesticides, so posting, notification, and reporting laws do not apply. The lack of registration requirements often means the products base their efficacy information on testimonials, as opposed to scientifically conducted research. Even those claims that appear to have been based on well-designed tests are usually not published in peer-reviewed journals or similarly reputable outlets.

Consequently, it is difficult to find independent evaluations of the statements made to justify the use of a product or technique.

Absent well-grounded information to support the effectiveness of an alternative method for mosquito control, the public health threat presented by many species of mosquitoes requires a reliance on traditional means of IMM as the prudent course of action. The standard approach relies on the following well-described, well-understood general principles including:

- Surveillance to determine the nature of the actual, or potential, mosquito problem
- Source reduction, often through water management, to eliminate breeding habitat or opportunities to reduce the number of mosquitoes requiring some form of management
- Larval control to prevent adult females from emerging, thus reducing any biting threats
- Adult control to eliminate those mosquitoes that manage to reach adulthood in numbers large enough to be a public nuisance or health hazard
- Public education to support source control and emphasize the public need for the vector control course of action adopted by the agency

A well-rounded mosquito control program will also be alert to advances in the state of science and may find opportunities where new control efforts can be tested without sacrificing public well-being.

2. Surveillance

2.1. Landing Rates

An often used method of determining whether there is a mosquito problem in an area has been to measure parous landing rates. Human subjects are used for pre-determined amounts of time to see how often hungry females will land on exposed body parts; potentially capturing the landing mosquitoes using an aspirator (University of Florida, undated). Although each subject is different in how he or she attracts mosquitoes, this kind of information obviously relates clearly to potential discomfort from mosquito biting for those exposed to the conditions of the test.

With regard to biting discomfort, it has been argued that landing rates are a much more precise means of conducting surveillance, opposed to other kinds such as traps. This is due to its clear relevance to the problem. Crans (1976) demonstrated that landing rates also correlate better to received complaints than New Jersey light trap data (see below for a discussion of New Jersey light traps). However, there are risks to the subjects of landing rate experiments, especially if the mosquitoes of concern may be carrying diseases. Some agencies, such as the Harris County Mosquito Control Commission, Texas, continue to use these kinds of data on a less frequent basis or for specialized reasons, such as repellent testing means (Harris County, 2002).

2.2. Mosquito Egg Surveys/Oviposition (Gravid) Traps

Large populations of important disease vectors can be monitored by providing them with suitable larval habitat, and then monitoring that habitat for subsequent use. Oviposition jars are useful tools for collecting information on many container-breeding mosquitoes, such as the Asian tiger mosquito (*Aedes albopictus*), the yellow fever mosquito (*Ae. aegypti*), and the tree hole mosquito (*Ochlerotatus triseriatus*) (Service, 1976). Egg counts from oviposition jars are good predictors of the larval populations of container-breeding mosquitoes that can be expected to hatch after the next rain. This was widely used during an attempt in the 1960s to eliminate *Ae. aegypti* from the Americas (Soper, 1965; Donaldson, 1965). Ovitrap use was reinstituted in the 1980s to trace the progress of *Ae. albopictus* across the US, following its discovery in Texas (Moore et al., 1990). A more recent innovation in ovitraps was reported by Scott and Crans (2004). *Oc. japonicus* was monitored using small blocks of polystyrene, placed in appropriate aqueous habitats. This species readily used the polystyrene as oviposition substrates, and the blocks were easily removed from the sampling sites for examination to determine the presence of eggs.

Oviposition traps or gravid traps are available through some supply companies. These devices are similar to oviposition jars in that they provide a black plastic container partially filled with odorous water as an attractant for female mosquitoes seeking polluted water as suitable oviposition habitat. The traps collect adult mosquitoes, rather than eggs, as the female mosquitoes are sucked into a net by a small fan motor before they can oviposit. Oviposition traps are very selective for female *Culex* mosquitoes and are, therefore, increasingly used for WNV surveillance. Gravid traps appear to attract mosquitoes over longer distances than CDC traps do; CDC traps imitate meal sites by emitting carbon dioxide [CO_2] (CDC, 2001).

Similarly, an on-going project to more closely define *Culex spp*. distributions and ecology in the northeast US has used oviposition trays to estimate the density of parous mosquitoes. The hypothesis is that the number of egg rafts in a sampling basin should be proportional to the number of egg-laying mosquitoes with access to that basin (A. Spielman, Harvard School of Public Health, personal communication, 2004).

2.3. Larval Surveys

Larval surveys sample mosquitoes during their immature stages before they have the opportunity to disperse as adults. Such sampling is an element of all comprehensive control programs (Goddard, 2003). Graduated dippers are often used, although larvae numbers are not adjusted for sample volumes (W. Crans, Rutgers University, personal communication, 2004). The most esoteric and innovative dipping tool may be a flat-weighted metal can with a string attached, which is an essential tool for collecting samples from storm drain ports protected by heavy metal gratings (Musa, 2002).

Estimates of population densities of larvae can be determined by counting the number of larvae on a per-dip basis. Presence-absence determinations are also useful in making control decisions. By noting numbers of larvae of each life stage, the investigator can estimate when mosquitoes will emerge and what control efforts should be most effective. For example, large numbers of pupae indicate that a large number of adults will emerge within a few days. Large numbers of pupal skins floating on the surface is a sign that adult mosquitoes have recently emerged. Larval species identification will be useful in selecting the most appropriate control measures and associated agents (O'Malley, 1989).

2.4. Adult Surveys

Adult mosquito surveillance, a very basic tool in mosquito management, provides information on mosquito abundance and mosquito-borne disease prevalence. It also measures the effectiveness of larval control measures (Goddard, 2003). Information that can be gained from standard routine adult mosquito surveillance includes:

- Estimates of adult mosquito population density and distribution.
- Identification of breeding sites.
- Identification of sites where larviciding efforts need to be increased.
- Detection of mosquitoes infected with West Nile Virus (WNV), St. Louis encephalitis (SLE), or Eastern equine encephalitis (EEE).

Equipment needed to collect adult mosquitoes is generally more complicated and expensive than that required for collecting larvae. Adult mosquitoes are very fragile, readily losing legs, scales, and wings when handled roughly, making identification difficult or impossible. For example, sweep nets are occasionally used, but these have great potential to damage the caught specimens (University of Florida, undated).

2.5. Daytime Resting Stations

Although it may not be commonly used by all agencies, a standard means to sample adult mosquitoes, especially *Anopheles*, is to mimic their daytime resting points, such as houses, barns, sheds, bridges, culverts, hollow trees, overhanging cliffs, and foliage (LMCA, 1993). Counts of mosquitoes utilizing natural daytime resting shelters can give a good indication of population density. The mosquitoes are often collected with an aspirator. In areas where no resting shelters are found, artificial shelters such as wooden boxes can be placed to allow for routine sampling (Service, 1976). Many mosquitoes that do not usually bite can be collected in this way. *Culista melanura*, the amplification vector for EEE, is routinely sampled for using resting boxes during the times of concern (Crans, 1995).

2.6. Light Traps

Light traps are a staple of almost all mosquito control programs. The CDC trap, developed by the Centers for Disease Control and Prevention (CDC), is widely used for adult mosquito surveillance. Mosquitoes are attracted by CO_2 emissions, imitating large creatures' exhalations, and are then sucked into a net at the bottom of the trap by a fan. The traps are usually set at dusk and collected at dawn (Reiter, 1983). Only select species of mosquitoes are attracted and catches tend to be smaller during a full moon. CDC traps are widely used for arbovirus surveys (CDC, 2001).

The New Jersey light trap is a larger metal device, usually located at a permanent sampling station. This trap is often equipped with a timing device that turns it on during selected hours on certain days of the week. It works by attracting mosquitoes to the light and sucking them into a jar containing a killing agent (Mulhern, 1942). Some see New Jersey light traps as being less effective traps, as they may catch fewer mosquitoes than baited CDC light traps set at the same position; however, as species composition and relative, not absolute, numbers are the important aspect to light trap data analysis, the difference between the traps in this regard is viewed by others as inconsequential (W. Crans, Rutgers University, personal communication, 2004).

2.7. West Nile and Other Arboviral Surveillance

Effectiveness of mosquito-control programs where mosquito-borne diseases are a concern clearly depends upon early disease detection and prompt, skilled response. Testing for arboviruses in vertebrate blood is an important surveillance tool, as is testing of dead bird tissues and pooled samples of mosquitoes (U. Florida and AMCA, 2004). Mosquitoes are tested in groups for efficiency, as the infection rate for individual mosquitoes is often very low, even when disease is rampant, the sampling of mosquito tissues in groups increases chances of detecting a virus in the species of interest (ASTHO, 2004; ADAPCO, 2004a; MAS, 2003). Molecular biology tools have been adapted for use in arbovirus detection. Enzyme-linked immunosorbent assay (ELISA), enzyme immunoassay (EIA), and polymerase chain reaction (PCR) methodologies for testing samples for WNV, SLE, EEE and other arboviruses generally give results within in a day or two. In fact, some of the EIA-based kits such as VecTest and RAMP are extremely easy to perform and give almost instantaneous results (ADAPCO, 2004a; MAS, 2003). In addition, some state and university labs have virus isolation and identification capabilities wherein the actual virus from mosquito, bird, human, or animal tissue is grown in the lab. The advantage of culturing the tissues is that it may be possible to isolate and identify a virus, or viruses, other than those tested for by the specific molecular biological probes.

Regarding laboratory needs, ELISA and EIA tests can be performed with the aid of kits and machines in places with standard laboratory capacity. PCR requires more extensive machinery and expertise, but still can be performed in biosafety level (BSL) 2 labs. For all three of the above tests (EIA, ELISA, PCR), when testing for evidence of WNV, BSL 3 is not required; however mosquito “grinding” and other steps in the process should be performed in a biological safety cabinet to avoid breathing the aerosol.[1] Virus isolation and identification, on the other hand, is considerably dangerous and should be conducted only in BSL 3 facilities (R. Pollack, Harvard School of Public Health, personal communication, 2004).

2.7.1. Communicating with other Professionals

State-level arbovirus surveillance personnel maintain frequent contact with public health and veterinary laboratories to collect and report information on mosquito-borne arbovirus activity as an extension of their public health responsibilities (see, for example, NYSDOH, 2001). In addition, mosquito-control personnel similarly contact local health-care personnel and veterinarians for information concerning arbovirus activity in the area, in order to determine if mosquito control efforts will be needed. If local surveillance identified suspected cases, state-level health authorities are informed, as they usually have statutory authority regarding the declaration of health emergencies. The duplication of effort is designed to increase opportunities for early virus detection. It is important to note that not all cases of encephalitis are mosquito-borne. Caution must be exercised in reacting to initial reports, and appropriate agencies need to work closely to get laboratory confirmation of suspected cases (CDC, 2001). The State of New Jersey has established a computer-posting capability for key mosquito parameters. This allows mosquito control professionals in New Jersey to use regional data to determine the significance of locally-collected information. In addition, the data sets are analyzed for temporal trends by academics and State-level professionals, which also generates additional information upon which the local organizations are able to base control decisions (W. Crans, Rutgers University, personal communication, 2004).

2.7.2. Sampling Wild Bird Populations

EEE, SLE, and WNV are all examples of viral diseases of wild birds that can be transferred to humans, and other vertebrates, by mosquitoes. In many states, health department personnel, or even pesticide applicators, collect blood from birds on a regular basis to monitor for virus levels in the avian population prior to human involvement in the disease. Viremia, viruses in the blood stream, are too short-lived to be of value for such testing; as such, the intent is to detect antibodies to the virus, which signal prior infection. Thus, if a wild bird was infected with a mosquito-borne virus at some time over its life-span, serological results will be positive. However, the positive result does not indicate time of exposure, as antibodies remain detectable in bloodstreams for years, often permanently. Therefore, information from hatch-year or birds that previously tested negative is much more informative, indicating that the bird recently, or locally, acquired the infection (CDC, 2001). This kind of monitoring is not especially common, especially in the northeast US.

Young birds can be taken from the nest, bled, and returned to the nest. Bleeding nestling birds has some advantages, but timing is critical and care must be taken not to injure the young birds. Sampling personnel must also ensure that the adult birds do not abandon the nestlings after they have been bled. An obvious advantage to bleeding nestling birds is that the age and travel history of the nestling is known, and, therefore, a positive result can be tied to a specific time frame and specific geographical location (CDC, 2001). Appropriate permits are required for this kind of sampling.

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[1] Tests for Eastern equine encephalitis (EEE) require BSL 3 lab facilities no matter which test is being used.

2.7.3. Sampling Sentinel Flocks

Sentinel flocks of chickens, quail, pheasant, or other birds can be retained in outdoor cages in specific sampling areas and bled periodically to monitor arbovirus activity. These sentinel birds are sometimes raised in a mosquito-free environment; in the northeast US, it is more common to test the birds prior to placement to ensure that they have not been exposed to arboviral activity elsewhere. If the sentinel bird tests positive after being placed in an area, it is a sure sign of arbovirus activity in the area. A supply of unexposed birds should be readily available to replace those that become infected, although often flocks do not accept new pen mates (CDC, 2001). Therefore, continuing surveillance may result in the introduction of confounding factors, as the infected birds may be the source of new infection in the flock,. To adequately sample large areas requires numerous sentinel flocks, so this method can be costly.

In addition, the time for the birds to seroconvert can sometimes be so long as to make the test irrelevant as a means of determining active virus activity. Seroconversion is most probably virus dependent. Crans (1986) found that flocks did not seroconvert during an EEE exposure. In Florida, the technique was very successful working with SLE (Day and Carlson, 1985). Walsh (1983) recommended it for Western equine encephalitis in California. Stivers and van Essen (2004) reported success in sentinel flock response to WNV, while, on the other hand, Suffolk County experienced notable failures in its 2000 efforts to detect WNV with local chicken flocks (D. Ninivaggi, SCVC, personal communication, 2003).

2.7.4. Wild Bird Sampling Methods

Mist nets, baited traps, or cannon nets can be used to capture juvenile and adult birds alive. The appropriate state and federal permits are required before collecting birds with any of these methods (Komar, 2001). Furthermore, banding permits are required if one wishes to band birds before they are released; capture-recapture data are useful in determining populations sizes, and can lead to infection rate calculations.

Mist nets are perhaps the most common means of collecting wild birds. The most popular nets are about 40 feet long and 7 feet high, commonly supported by metal poles and suspended 4 to 5 feet above the ground. These nets are made of materials that are difficult to see, causing the birds to become entangled in the fibers. The mosquito-control worker can then remove the birds, draw blood samples and release them at the site (Komar, 2001). Some districts band some or all of the birds prior to release (McLean et al., 1983).

Baited traps are especially useful for trapping sparrows, grackles, doves, quail and pigeons. The bait, grain, seed, or both, is scattered around the trap to attract birds. Additional bait is placed in the trap to lure the birds inside (Komar, 2001). Bait traps are usually equipped with large hinged openings so that the trapped birds can be removed easily. Elevated bait traps, which may be more attractive to some species of birds, are used where cats or other predators pose a threat.

Cannon nets can be used to collect large numbers of blackbirds, pigeons, ducks, cowbirds and other birds that travel and feed in large flocks. They are the only realistic way to capture some species alive. The cannon net is designed so that one edge is anchored to the ground and the other is attached to rocket projectiles that carry the net over feeding birds (Komar, 2001). Because cannon nets are expensive and require several people to remove birds quickly to avoid injuring them, this is probably the least-used trap method.

Increasing rates of infection in bird populations may be useful in determining threat levels for people (Komar, 2001). However, the data may be of more or less value, depending on the state of knowledge regarding the characteristics of specific species. For instance, a study in Louisiana reported that infection rate data drawn from cardinals and sparrows appeared to correlate with other indicators of WNV infection, especially mosquito pool testing, while the rates generated from other trapped bird species did not (Augustine, 2004).

2.7.5. Predicting Disease Incidence

Cornell University has received a grant from the National Oceanic and Atmospheric Administration (NOAA) to study climate interactions with mosquito populations that are responsible for transmitting diseases, such as WNV. This New York State-based effort is intended to be transferable to other areas of the country, and will be adaptable enough to accommodate viruses that have not yet been introduced to the US, as well as those that already threaten human health here. By studying a few key climatic factors, the researchers anticipate developing a decision tree that will allow for early warning of risks of disease outbreaks (F. Crawford, Cornell News Service, press release, July 12, 2004).

3. Repellents

The products listed below are considered minimum risk compounds by USEPA and therefore do not require federal registration under FIFRA. Further, in most states, these products are not classified for regulatory purposes as pesticides, so posting, notification, and reporting laws do not apply.

Unfortunately, some of the unregistered products base their efficacy information on reports and testimonials that are not published in scientific or professional journals, and almost are addressed through any peer-reviewed process. For example, the Entomological Society of America provides just such an outlet for unbiased scientific evaluations. *Arthropod Management Tests* publishes short reports on preliminary and routine screening tests for management of arthropods which may be beneficial (e.g., parasitoids, predators and diseases of pests, honey bees, silkworm, etc.) or harmful (e.g., pests and disease vectors of plants, animals, and humans). Much greater credibility would be garnered for some of these products if such tests were independently performed and published.

3.1. Plant Oil Concentrate

EcoSmart Technologies Corporation has developed a product called EcoExempt IC, which is an insecticide concentrate containing a blend of plant oils which is labeled for outdoor yard and barrier treatment for mosquitoes (EcoSmart Technologies Product Brochure, 2004). The manufacturer provided an unpublished report on preliminary testing of this product against a limited number of mosquitoes in the laboratory (Arnason, 2004). That study reported immediate knockdown of flying mosquitoes and residual effects of the product, killing mosquitoes introduced into cages previously sprayed with the product ten minutes earlier. In addition, the technical director of the EcoSmart Corporation, a Ph.D. entomologist, said that EcoExempt IC is being used in mister systems around homes for mosquito control (see section below on automatic misters). According to the technical director, a drawback in the use of EcoExempt IC is that when used at the highest label rate the product may damage the plastic parts in the application equipment, though the problem can be alleviated by lowering the application rate.

3.2. Garlic-Based Repellents

Garlic and garlic oils have received recent attention as alternatives to synthetic pesticides for mosquito repellent, and, sometimes, pesticidal purposes.

There are at least two garlic-based adult mosquito repellents. The Mosquito Barrier^R or the Garlic Barrier^R, from Garlic Research Labs of Glendale, CA, reportedly kills adult mosquitoes and repels them from treated areas (Garlic Research Labs Product Brochure, 2004). The company claims that the product, when mixed with canola oil, will kill mosquito larvae in aquatic environments. The company website reports the results of a study conducted by the East Baton Rouge Parish Mosquito Abatement District in which garlic oil in water at a concentration of 10,000 ppm killed 82 percent of mosquito larvae in four (4) hours and 100 percent in 24 hours (Garlic Research Labs *Scientific Study of Mosquito Barrier^R on Mosquito Larvae*, 2004). The manufacturer published a test of Mosquito Barrier^R used as a repellent against adult mosquitoes (Brock, 1995). It reports that garlic juice, diluted to 0.99 percent, repelled 93-95 percent of mosquitoes for 1-2 weeks. The single larval control study cited by the Garlic Labs on their website fails to adequately address the possibility that larval mortality was due to the vegetable oil used as a dilutent, instead of the garlic itself. As the repellent is a water-based product, its efficacy after a rain event may be lower.

Another garlic-based product is called “Mosquito and Gnat Scat”, which is marketed as a flying insect repellent by Dr. T’s Nature Products, Pelham, GA (Dr. T’s Nature Products, 2004). Mosquito Scat^R is an herbal oil preparation containing three oils as active ingredients: lemon grass oil, peppermint oil, and garlic oil. The product is a dry granular substance easily applied from a sprinkler cap on the bottle. The label says the product can be used around homes, lawns, pools, patios, water gardens, tennis courts, picnic areas, and campsites. The manufacturer claims that Mosquito Scat^R is effective on many flying insects, not just mosquitoes, and one application lasts three weeks (Dr. T’s Nature Products, 2004). The manufacturer provided results of a study on the product’s effectiveness performed by personnel at Georgia Southern University (Moye, 2004). They reported that the product was somewhat effective when used on suburban lawns. Mosquito traps in suburban areas showed that, for each trial, the treated site had more days of fewer mosquitoes than the untreated site. However, overall for both suburban and rural test sites, there were no significant differences in mosquito numbers in the comparison of treated vs. untreated areas (Moye, 2004).

One of the touted benefits to garlic products is the promise of replacing synthetic chemicals with an apparently less-harmful, natural material, especially when there were no overt health threats from the mosquito infestation. However, generally, garlic repellents do not appear to have worked well at discouraging mosquitoes, especially when densities were higher.

3.3. Ultrasonic Mosquito Repellents

Hand-held electronic devices relying on high-frequency sound to repel mosquitoes continue to come to the marketplace. They often claim to work by mimicking wing beat frequency of a male mosquito or even the wing beat frequency of a hungry dragonfly. Scientific studies have repeatedly shown that electronic mosquito repellers do not prevent host-seeking mosquitoes from biting (Foster and Lutes, 1985; Schreck et al., 1984; Schreiber et al., 1991; Crans, 1996). In fact, the American Mosquito Control Association was so upset with what its members perceived of as unsubstantiated product claims that it began, eventually unsuccessful, legal proceedings against some manufacturers of these products on the basis of false advertising (Curtis, 1994). The Federal Trade Commission did take notice of the claims, however, and has required alterations to the language that so upset mosquito control professionals.

3.4. Scent-Based Repellent

The Mosquito Cognito^{R} emits a chemical called Conceal^{TM} that, according to the manufacturer, has a unique scent-blocking ability (Mosquito Cognito Machine Product Brochure, 2004). Conceal^{TM} purportedly binds to mosquito olfactory receptors and blocks their ability to smell people and animals. The Mosquito Cognito^{R} looks something like a square suitcase or ice chest, and can be placed outside on decks or porches where people are gathered. One unpublished, but apparently reputable, study of the device's effectiveness was performed by the University of Florida Medical Entomology Laboratory at Vero Beach, FL in 1998. That study concluded that the Mosquito Cognito^{R} reduced mosquito landings on humans on a raised platform, such as a deck or porch, located at least nine meters away from mosquito habitat by about 75 percent when used properly. It concluded that, "while it can keep distant mosquitoes from locating people, it cannot prevent nearby mosquitoes from locating people by vision or by the person's thermal emissions. For this reason, it is inappropriate for use within mosquito habitat" (University of Florida, 1998).

4. Mechanical Controls

New Mountain Innovation Company has produced a larvasonic acoustic device, which is expected to kill larvae using sound energy (New Mountain Innovations Specifications Brochure, 2004; Harlan, 2004). According to the manufacturer, the device gives off sonic energy as a short (less than 15 seconds), minimal energy burst of about 400 Watts that causes air spaces within each larvae to resonate violently enough to kill them by disrupting internal membranes and organs. There are several adaptations of the technology:

- a hand-held unit, about the size and shape of a weed-eater, for ditches and wetlands,
- a canal-pod unit to be towed behind a boat in canals, and
- a storm drain unit.

These devices are relatively expensive ($4,000 and up) and, according to the manufacturer, are limited in their "killing power" to a range of 3 ft to 25 ft in diameter, corresponding with the model being used. Therefore, large-scale use of larvasonic acoustic devices is probably not feasible. In addition, although the manufacturer claims these have no effect on non-target organisms, controlled lab testing against other closely related non-target aquatic insects or other invertebrates has been limited; and there has been only limited field testing so far (Harlan, 2004).

Limited testing was undertaken using the Larvasonic SD2001™, an early version of the larvasonic devices, by the New Jersey Mosquito Control Commission. Testing in a wading pool found the machine killed *Cx. pipiens* larvae better than expected, but did not meet expectations for *Oc. triseriatus* larvae. The report cautioned that non-target organism impacts were not considered in this test (Rainey and O’Malley, 2003).

5. Traps

Special traps have been developed in the last few years that attract and catch large numbers of mosquitoes, thus removing them from a fairly wide radius around the trap (Harlan, 2004). Brand names of such traps include the Mosquito Magnet^R, Mosquito Megacatch^R, the Flowtron Power Trap^R, the Dragonfly^R, the Lentek Mosquito Trap^R, The Lentek Eco Trap^R, Mosquito Deleto^R, and the SonicWeb^R. This technology is developing rapidly and there is considerable variability in the way these traps function. The vast majority of these traps use CO_2, produced either through the combustion of propane or via a CO_2 cylinder and released at between 350 ml and 500 ml/min. The plume of CO_2 produced mimics human exhalation and makes these traps specific for capturing blood-feeding insects. Therefore, non-target insects such as moths and beetles will not enter the trap and cause damage to the fragile mosquito specimens. The CO_2 is often synergized with 1-Octen-3-ol, a derivative of gasses produced in the rumen of cows, to increase attractiveness by several orders of magnitude. The 1-Octen-3-ol is slow-released at a rate of approximately 0.5 mg/h. The traps also vary in the manner in which mosquitoes are trapped/killed. Some traps have a fan to suck insects into a collection chamber or bag, while others contain a glue board to catch the insects. Several of these traps claim to "cover" or "protect" about a 120-foot radius around the trap in still air.

One study showed that the Mosquito Megacatch^R and Mosquito Magnet^R caught several thousand mosquitoes each in 24 days. The Lentek Trap^R caught slightly over 1,000 in the same time period, while the Flowtron^R, Dragonfly^R, Mosquito Deleto^R, and SonicWeb^R caught less than 500 each (Smith, 2004). Work by Kline (2002) demonstrated that propane-powered traps can capture up to 71 percent of host-seeking mosquitoes released into a *confined* area. Kline states these traps are environmentally friendly and have potential as mosquito management tools. Further research is needed to determine if these traps reduce the rate of human biting when deployed; questions have also been raised about whether they attract more mosquitoes than actually enter the traps. Most mosquito professionals are of the opinion that it is impossible for any of the traps to catch all of the host-seeking mosquitoes in a given area under nearly all conditions.

New Jersey is researching the potential for these traps to be used as monitoring devices. Although they are not capable of removing all of the mosquitoes from an area, they collect a sample of the mosquitoes, and in a condition that allows them to be identified – which is very important in mosquito monitoring. Unlike traditional traps, these newer traps can run day and night and so may attract a greater variety of species than New Jersey light traps or CDC traps do on their own. Every trapping method exerts a certain bias on the population sampled; it is unclear how these kinds of traps under- or over-sample particular species (W. Crans, Rutgers University, personal communication, 2004).

6. Biological Controls

The use of biological organisms, such as parasites, predators, or pathogens, to control mosquitoes is termed biological control or biocontrol. Many biocontrol agents are host-specific, which reduces impacts on non-target organisms. With the exception of bacteria (see below), these agents are generally expensive to propagate and difficult to transport to the field. In addition, they thrive only within a narrow range of environmental parameters and may require periodic reintroduction, as many are not self-sustaining in the aquatic habitat. In addition to bacteria, there are various species of microsporidia, fungi, parasitic nematodes, copepods, and even other mosquito species, which may kill mosquitoes (Barnard, 2003).

In addition, there are means of biologically modifying the mosquitoes themselves. Genetic controls of mosquitoes have been considered for over 20 years (Joslyn, 1980). With the sequencing of mosquito genomes either accomplished or possible, transgenic control measures are also being considered (Tabachnick, 2003).

6.1. Bacteria

The bacterial product, Bti (*Bacillus thuringiensis* var. *israelensis*), has been available for more than 25 years and a similar product, Bs (*Bacillus sphaericus*), has been on the market for several years. These products are extensively discussed in Book 5 Part 2 and Book 4 Part 1 of this Literature Search. Their toxicity is discussed in Book 6 Part 1 and Book 7.

Bti and Bs are very successful biological control agents for mosquitoes. Bti is also effective in killing black flies and several species of midges, but has no adverse effect upon other insects, fish, or laboratory animals. Bti is available in wettable powder, liquid, granular, capsule, and briquette formulations. It has also been formulated with growth regulators and monomolecular films (USEPA, 1998).

Early stage larvae are more readily killed by Bti than late stages. Lower dosage rates can be used when larvae are in their early stages of development, but the higher recommended dosage should be applied to populations of late third and fourth stages. The higher the concentration of spores at the surface, the greater the likelihood that the older larvae will pick up a few spores. Bti is less effective against the late instars.

Bti attacks the intestinal tract cells of mosquito larvae, making them unable to absorb food, causing larvae to die within 8 to 12 hours. As these products must be ingested by actively feeding mosquito larvae, they have no effect on 4th instar larvae or pupae, unless they fed upon it before pupating. Both bacterial products break down when exposed to ultraviolet light, but work well in clear to polluted water. At operational concentrations, testing submitted to regulators such as USEPA has shown very little, if any, toxicity to mammals or fish (USEPA, 1998).

The effectiveness of these products is well known. One recent study in Thailand demonstrated that treatment of water sources with Bs to kill larvae resulted in a substantial reduction in adult mosquito populations within two weeks. As part of that study the authors noted what appeared to be a rapid build-up of resistance to Bs (Mulla, 2001). Others have reported this phenomenon as well (Oliveira *et. al.*, 2004). This finding may be very significant to mosquito control programs in the US since Bs is widely used as a larvicide in WNV prevention programs aimed at *Culex* mosquitoes.

In many species of mosquitoes, younger larvae will be feeding actively for a week or more and, therefore, have plenty of opportunity to ingest a few Bti spores, even when applied at the lower dosage rate. The higher application rate should be used when larval population density is high, regardless of the predominant instar present. Mosquito larvae are very efficient filter feeders. Large numbers of larvae will quickly filter out all of the spores applied at low rates before all larvae have a chance to feed on the material (USEPA, 1998).

The higher recommended rates should be used in water polluted with septic tank discharge or habitats with a heavy growth of algae. These waters generally have higher concentrations of suspended food particles, with which Bti spores are competing. Using the higher dosage rate increases the chance that larvae will pick up at least some of the spores along with the food they are feeding upon. Another alternative for polluted water is Bs (Mittal, 2003).

Granular Bti is generally applied to areas covered by thick vegetation, such as salt marshes and weedy ditches. It has also been used in flooded pastures, irrigated fields, and tire piles. If granules are applied to large areas of open water, winds can push them against one shore. Granular formulations consist of spores attached to a carrier made from ground and sized corn cob particles. The carrier floats, keeping much of the material at the surface where most larval feeding occurs (Valent Biosciences Corp., undated product brochure). Different companies make different size corn cob particles. As a rule, smaller particles can fall through thick grass better, but may be more likely to stick to wet blades. Larger granules can be broadcast further and are less affected by wind.

Ground application of granular Bti can be made with many types of manual or mechanical seed or fertilizer spreaders that use a whirling disk. Horn seeders have not proven to be as effective (J. Goddard, Mississippi Department of Health, personal communication, 2004). Generally, recommended application rates range from 2 to 10 pounds per acre. The actual rate required at each site is largely dependent upon the same factors discussed for application of liquid formulations. Generally, treatment should be repeated every seven days.

Bti is also formulated into briquets. One brand name is Bactimos^{R}. They are usually more expensive than liquid and granular formulations. Cost per acre is generally about $15-$55. However, these floating briquets will give up to thirty days of treatment under normal conditions (Valent Biosciences Corp., undated product brochure). Briquets can be used in many habitats where mosquitoes breed. They can be anchored to tree limbs or weighted with string to prevent them from floating away. Usually, one briquet will treat about 100 square feet of water surface, regardless of depth. Up to four briquets per 100 square feet may be required in heavily polluted water. Briquets can be applied to areas that flood during rainy periods, such as woodland pools. These briquets will float when the area is flooded, releasing Bti. Effectiveness of the Bti will not be reduced by dry periods.

6.2. Tadpole Shrimp

A new biocontrol agent that shows promise for larval mosquito control is the tadpole shrimp, *Triops newberryi*. Tadpole shrimp (TPS) are freshwater crustaceans adapted to temporary bodies of water in arid regions. These creatures have been mentioned as possible mosquito biocontrol agents for a long time, but have just recently been studied intensely. TPS are of special interest because their eggs can withstand drying and will hatch weeks or months later when fields are flooded. A recent study in irrigated fields in southern California showed that TPS populations were established in the fields after a single introduction of eggs or mature TPS. As compared with areas of the field without TPS, the presence of high numbers of TPS reduced mosquito larvae by 73 to 99 percent (Su, 2002). Further testing is needed before TPS can become widely used in mosquito control, and, at present, tadpole shrimp are not commercially available. The sources of TPS eggs in published studies have been soil samples from dried up ponds in California.

6.3. Fish

Fish have been widely used in mosquito control for decades and are effective biocontrol agents because they catch and eat mosquito larvae in a variety of aquatic environments. Many kinds of fish are effective for mosquito control, however, top minnows (family Poeciliidae) and killifish (family Cyprinodontidae) are used most frequently because they are small and are readily available in the wild or from commercial sources. In salt marshes, water and vegetation management methods are often employed to improve killifish and minnow habitat and/or allow for greater consumption of mosquito larvae by these fish (CDC, 2001).

One mosquito-eating fish (*Gambusia affinis*), a top minnow, has been so effective for mosquito control that it has been used more than all other species of fish combined. *Gambusia* is particularly useful because it thrives in a broad array of aquatic habitats including freshwater or brackish water, and clean water or polluted water; and it tolerates a wide range of temperatures (Meek, 1993). Control with *Gambusia* is usually rapid, though maximum control may be achieved only after the fish have had a month or two to build up their numbers.

New Jersey, for example, grows *Gambusia* at a state-operated hatchery to ensure there are enough fish to stock its freshwater environments (W. Crans, Rutgers University, personal communication, 2004). In Suffolk County, SCVC purchases *Gambusia* from commercial sources. SCVC does not need to stock salt marshes, as there is natural recruitment from the estuaries into the marshes (D. Ninivaggi, SCVC, personal communication, 2004).

6.4. Reputed Mosquito Predators

There are people who believe that certain naturally occurring predators can control mosquito populations. Charles Wurster, PhD, for example, commented in the Scoping for this project's Environmental Impact Statement that "birds, especially swallows, and bats consume extremely large quantities of insects, especially mosquitoes" (Cashin Associates, 2002). Others with less scientific training have noted for decades that particular birds, bats, and predatory insects may be able to control mosquito populations.

There are about 1,000 species of bats worldwide, approximately 45 species in the US. Most bats worldwide feed on insects, although a few species eat fruit, flowers, blood, or even small fish and rodents. All US species of bats eat either insects or nectar. Various publications and websites indicate that bats help reduce insect populations, such as mosquitoes, and that bat colonies should be encouraged in an area by installation of "bat boxes". In fact, during the 1920s several large bat towers were constructed near San Antonio, Texas, and Key West and Tampa, Florida, with the intent of controlling malarial mosquitoes with high numbers of insect-eating bats (Mitchell, 1992). Mosquito populations were not reduced, but the large accumulation of guano was sold at a profit.

An oft-quoted figure is that bats eat up to 600 mosquitoes per hour (Mississippi Museum of Natural Science Newsletter, 2004). However, this is based upon research conducted in the late 1950s indicating that bats released in a room filled with mosquitoes could catch up to 10 mosquitoes per minute (Griffin, 1960). No other insects were in the room. The results have been extrapolated to suggest the "600 mosquitoes per hour" number (Crans, 1996; Tuttle, 1988). Research since that time, as well as the testimony of persons studying bats, has shown that bats are opportunistic feeders and mosquitoes make up a very small percentage of their natural diet (Crans, 1996; Whitaker, 1972; Whitaker and Clem, 1992; Corrigan, 1999). Little brown bats feed on soft-bodied insects such as moths, flies, caddisflies, and leafhoppers (Whitaker, 1972). The larger big brown bat is opportunistic, and preys mostly upon beetles, such as ground beetles, June bugs, cucumber beetles, and other beetles and insects (Whitaker, 1972). The Mexican free-tailed bat consumes primarily moths and beetles (Corrigan, 1999). Bobby Corrigan who studied bats for his Master's Thesis states that, while outside bat roosts counting bats for his project, he was "eaten alive" by mosquitoes. His opinion about bats in flying insect control is as follows: "Relative to pest (insect) populations, whether or not the feeding of bats in our urban and agricultural communities provides any measurable benefit (or negative impact via consumption of good insects) is highly questionable" (Corrigan, 1999).

Installation of bat boxes, houses,)carries with it the risk of bat-associated rabies. In the last 40 years, most human cases of rabies in the US have resulted from bats. Since rabies is almost always fatal, the best ways to control it are:

- prevent human exposure, and
- prevent disease by anti-rabies treatment if exposure occurs

(CDC Brochure, 1998).

Since the CDC recommends "prevention of human exposure" to bats, municipalities should be cautious when considering the installation of bat boxes for mosquito control.

It has been known for years that purple martins consume large numbers of flying insects. Several references summarize the potential value of the birds in mosquito control (Mitchell, 1993; Kale, 1968; Grossman, 1990). Wade said that a single purple martin can eat 2,000 mosquitoes a day (Wade, 1966). Accordingly, many people erect complex bird houses to attract the birds. Wade apparently had little scientific evidence, such as examining stomach contents, to support his claims that purple martins eat 2,000 mosquitoes a day. An exhaustive study of the diet of purple martins revealed the following percentages of food items:

- wasps and ants – 23 percent;
- house flies and crane flies – 16 percent;
- stink bugs and tree hoppers – 15 percent;
- beetles – 12 percent; and
- a combination of unidentified butterflies, moths, and dragonflies – 34 percent

(Layton, 1969)

These data indicate mosquitoes and similar small, very light insects are not usually part of the purple martin's diet. James Hill, founder and one-time director of the Purple Martin Association, has said, "The number of mosquitoes that martins eat is extremely insignificant, and they certainly don't control them" (Grossman, 1990).

Dragonflies are predatory insects, that catch midges, mosquitoes, small moths, and even bees and butterflies. The use of dragonflies to control mosquitoes has been used in the town of Wells, Maine, where "dragonfly augmentation" was incorporated into their mosquito control program (Aronson, 2004; Town of Cranberry Isles, Maine, 2003). The Town raises and sells dragonfly nymphs to local individuals who want to use them on their property. The effectiveness of dragonflies in Wells is complicated by their concurrent use of mosquito Dunks^{R}, which contain Bti, an effective larvicide. The apparent success of the dragonfly release program could be due to larviciding with Bti. A professor of Zoology at the University of New Hampshire has been quoted as saying, "There is no scientific evidence that the program (at Wells, ME) has been effective" (Aronson, 2004). Dragonflies are difficult to rear in the laboratory for release, and they have a very long life-cycle, meaning populations cannot be quickly increased. In addition, dragonflies are free to fly about and therefore cannot be contained in the area where control is desired. The only scientifically sound assessment of the dragonfly/mosquito interaction is that they do, in fact, eat mosquitoes, and, therefore, reduce local mosquito populations to some extent. To what extent is not known at this time.

6.5. Other Organisms

The nematode parasite (*Romanomermis culicivorax*) is an aquatic mermithid worm that is host-specific to members of the mosquito family, Culicidae, parasitizing the larval stage. This parasite was at one time commercially available, approximately 20 years ago, and has been used in some areas for mosquito control with measured success (Giblin, 1987; Poinar, 1979). The parasite was marketed as "Skeeter Doom" by the Fairfield Biological Laboratories in Clinton Corners, New York, but is, apparently, commercially unavailable for a variety of reasons, one being the reduced viability of eggs during transport (Giblin, 1987). One major drawback to commercial development of parasites like *R. culicivorax* is the fact that mosquito larvae are not heavily infested by parasites in nature. Therefore, it is not possible to release a small number of the parasites to multiply and spread throughout a mosquito population. High rates of infection can be attained only by releasing very large numbers of parasites. The cost of producing such large numbers is, generally, impractical for mosquito control.

Copepods (Cyclopoid copepods—crustaceans) are predators of mosquito larvae and may be suitable biocontrol agents in breeding habitats where fish will not work, such as in the middle of thick aquatic vegetation and places which periodically dry up. Only the largest copepod species in the genera *Mesocyclops, Macrocyclops,* and *Megacyclops* are effective mosquito control agents; the numerous small species, common to many places where mosquito production is high, are not effective predators of mosquito larvae. The most common use of copepods for mosquito control is in discarded tires. They can survive in tires as long as the tires retain moisture, which can be months to years. The best species for use in tires is *Mesocyclops longisetus* (Meek, 1993).

6.6. Genetic Controls

For over 20 years, scientists have investigated whether the introduction of sterile mosquitoes into natural populations would serve as an effective means of control. Sterility is most often induced into male mosquitoes by chemicals or radiation. Functionally sterile males can also be generated through hybridization, although often the degree of sterility may vary for individual males, or through genetic incompatibility between a raised population and a wild population, again, it is not always the case that all individual pairings of such mosquitoes will be sterile. Because hybridization and genetically incompatible populations have associated failure rates, most genetic controls have depended upon reliable radiation, gamma or X-ray exposure, or chemical exposures to cause sterility in the population. Genetic decay may result in the laboratory insects. Genetic decay is a reduced fitness as a result of a decrease in genetic variability, influenced by laboratory conditions that do not lend themselves to continued natural selection. If genetic decay has not occurred in the laboratory insects, then the organisms can be released into the wild to prevent wild males from mating with available females. In order for this to occur, the sterile male population must swamp the wild population. The estimated ratio of introduced to wild mosquitoes is on the order of approximately 30 or 40 to one (Joslyn, 1980). This means this technique is only practical where the geographical area being treated is small and the population of interest is also small. Control of *C. pipiens* is a classic example of a successful implementation (Laven, 1967).

6.7. Trans-genetic Controls

The World Health Organization (1991) identified three goals that need to be met in order for transgenic control of malaria-carrying mosquitoes to be field-tested. They were:

The development of genetic engineering tools for malaria vectors

- The identification of effector genes that can block parasite transmission
- The development of a means of transmitting the genes into the natural populations

By 2002, with the sequencing of the *Anopheles gambiae* (Holt et al., 2002) and *Plasmodium falciparum* genomes (Gardner et al., 2002), it was apparent that the first two goals had been met. Tabachnick (2004) discussed how close the technology might be to meeting the third goal – that is, manipulation of the genetic code of *Anopheles* mosquitoes in order to reduce its competence as a vector.

The great dream, of course, is that the sequencing of these genomes might reveal genetic loci where manipulations of the genetic material could result in disruption of the disease. This could be through the derivation of a vaccine to prevent the disease, or drugs that defeat the parasite once infection occurs (Carucci, 2004). Others hoped that the new knowledge of the mosquito genome might lead to ways of preventing the mosquito from being able to acquire the parasite in the first place (Clarke, 2002).

Because genes are expressed as particular proteins/enzymes/polypeptides, the hope associated with genetic sequencing is that the determinants of much of an organism's physical being can be understood. However, environmental factors also play a large role in how the genetic code is expressed. This means, absent an understanding of the variability of gene expression, the sequence may have limited value (Hamer, 2002).

Tabachnick (2004) expressed concern that too little is known about mosquito gene expression and associate traits of concern, such as vector competence. He discussed how the WNV outbreak into North America clearly demonstrated the limits of knowledge concerning key elements of mosquito-borne disease. For this reason, he believes it will be some time before trans-genic mosquitoes can be used to control disease.

There is some disagreement on this point. Hemingway (2004), while admitting there are daunting tasks associated with distributing any genetic change throughout the target mosquito species, believes that the extremely fine-tuned relationship between the mosquito and the parasite offers many, somewhat readily-available opportunities for intervention, pointing out that, for example, a small change in stomach gut chemistry for the mosquito could stop parasite transmission. However, there are also suggestions that manipulating the mosquito genome reduces its fitness, so that these trans-genic organisms may not be able to compete with naturally occurring mosquitoes (Catteruccia et al., 2003).

Rasgon et al. (2003) suggest another means of addressing the problem. They also believe that it is unlikely that the genetics associated with vector competence can be manipulated with great success. For one, they point out that relatively few competent mosquitoes may be sufficient to maintain a disease as virulent as malaria in an affected area. This implies that the genetic manipulation must be close to universal to be successful as a control strategy. However, they believe that a different tactic, reducing mosquito lifespans by introducing susceptibility to another parasite, may be more effective. They argue that relatively small changes in the daily probability of survival for a vector may lead to a sufficient reduction in numbers to break the disease transmission process. This is because it is the old mosquitoes that bite twice that are the disease vectors. Rasgon et al. have a particular parasite in mind: *Wolbachia*. In fruit flies, *Wolbachia* tends to reduce lifespan by approximately half. A mosquito symbiont could prevent 100 percent of disease transmission, according to their model of mosquito population dynamics. Despite the advanced state of their theory, it does not seem likely to come to fruition in the near future.

7. Chemical Controls

7.1. Storm Drain Larvicides

During the recent WNV epidemic in the U.S., new emphasis was placed on larviciding storm drains and catch basins to kill *Culex* mosquitoes. One new development in this effort was the "re-shaping" of the Altosid® XR Extended Residual Briquets, methoprene, to fit through the standard storm drain grates used in most municipalities (see Section 7.3 for more information on methoprene) (Zoecon Professional Products Brochure, 2004). This makes them easier to apply because the grates don't have to be removed. These briquets generally treat 100 ft^2 of water, two ft deep. New Jersey state officials have requested local agencies not to use this formulation, however. The concern is that the long exposure period could result in methoprene resistant mosquitoes (W. Crans, Rutgers University, Personal communication, 2004).

In addition, Arro-gun Spray Systems Company has developed a machine called the "Mozzie" which can easily apply Altosid ® XR-G pellets into storm drains and catch basins. This formulation is intended to provide six weeks of control (Arro-Gun Spray Systems Brochure, 2004).

Both of these approaches have become relatively widely accepted in the mosquito control community over the past several years. This is because *Culex spp.* mosquitoes, which commonly breed in catch basins, are believed to be the primary vectors for WNV. Various Bs formulations, including VectoLex® WSP, a water-soluble pouch, are registered for use in catch basins for the control of mosquitoes, including *Culex spp*.

7.2. Monomolecular Films

Oils have been used as larvicides for over one hundred years. They were phased out of use due to toxicity to aquatic vegetation and other impacts to various kinds of non-target organisms. The aquatic ecological impacts from petroleum products are now well studied. The recently developed monomolecular film formulations, discussed below, are generally said to be environmentally friendly due to little to no impacts on aquatic flora.

Monomolecular films such as Agnique MMF^R and Arosurf^R reduce the surface tension of water, making it difficult for larvae, pupae, and emerging adults to attach to the surface, causing them to drown. They were developed to replace the original petroleum-based products. These products may also clog larval and pupal breathing tubes, interfering with air exchange. It is generally reported that these films have little or no toxicity to mammals or fish (Nayar, 2003).

Petroleum hydrocarbons such as Golden Bear Oil^R rest on the surface of the water and enter the breathing tubes of mosquitoes as they approach the surface to collect oxygen, causing them to suffocate.

A review of monomolecular surface films (MSF) for immature mosquito control was recently published (Nayar, 2003). The two commercially available MSFs, Arosurf^R and Agnique^R, are chemically identical and differ only in their purity and ability to mix with other larvicides. Arosurf^R and Agnique^R belong to a group of non-ionic surfactants, which are biodegradable surface control products that spread spontaneously and rapidly over the water. They are called monomolecular films because they form an ultra-thin layer about one molecule in thickness. A number of scientific studies showed that monomolecular surface films can be safely used for mosquito control in a wide variety of habitats, such as freshwater and saltwater marshes, pastures, ditches, sewage treatment vats and storm sewers, dairy waste ponds, and tree holes. They are especially useful in controlling late 4th instar larvae and pupae when most other commercially available larvicides and pupicides are less effective.

MSFs can be mixed with other larvicides for more immediate control of earlier larval instars, as well as late larval instars and pupae. MSFs may also be useful, particularly against chemically resistant mosquitoes (Nayar, 2003). The residual effect of most oil formulations for killing late stage instars and pupae is about 5-7 days.

Some disadvantages of MSFs include:

- they are nearly invisible on the water surface and require a time-consuming testing process to determine if they are still present,
- they are drawn toward vegetation and floating debris, and

- sustained winds tend to make the films pile up in localized areas.

7.3. Insect Growth Regulator - Methoprene

Active ingredients in Insect Growth Regulators (IGRs) disrupt the normal growth patterns that occur in an immature insect, in this case, a mosquito larva, as it molts. This interruption causes the insect to retain its juvenile or immature characteristics, thereby preventing adult emergence, which eventually kills the larva. IGRs may be used to control second, third and fourth instar larvae. Chemicals in these growth regulators affect only those systems found in insects and closely related arthropods, and have very little, if any, toxicity to mammals and fish.

Methoprene (Altosid) is a widely used IGR for immature mosquito control. The product was first registered as a conventional chemical pesticide in 1975, but subsequently reclassified as a biochemical pesticide (USEPA, 1991). During the re-registration process of methoprene in 1991, USEPA concluded,

> "Methoprene is of low toxicity and poses little risk to people and non-target species, with one exception. Methoprene is highly acutely toxic to estuarine invertebrates … (and) the only use of concern is the aquatic, mosquito larvicide involving the briquette formulation"

(USEPA, 1991).

However, the manufacturer addressed this concern by submitting new data to USEPA from an "estuarine invertebrate life cycle toxicity study" in 1996, on mysid shrimp (*Mysidopsis bahia*, in particular) (USEPA, 2001). Therefore, the current EPA-approved Altosid^R briquet label allows for its use in those areas which were once of concern—swamps, marshes, and tidal marshes (Wellmark, 2002).

Methoprene can be effective when used against any larval stage. Larvae do not die, but continue their growth process and pupate. Pupae that develop from exposed larvae will die and adults will not emerge. Methoprene (Altosid^R) comes in liquid formula (five and 20 percent), a new granular formula, 30-day briquets, and extended release briquet formulations.

Methoprene is especially useful in places such as storm drains, fountains, cesspools, waste treatment and settling ponds, abandoned swimming pools, and other man-made sites. Briquets can be tossed into the water. They will sink to the bottom and slowly release the IGR. The liquid can be mixed with sand and sprayed. Residual effects range from 7-10 days for liquid formulations, to 30-150 days for some of the briquets, depending on the formulation. Briquets are designed to withstand wet and dry periods to extend the residual effect through periods of heavy rainfall, flooding, etc. (Wellmark, 2002).

7.4. Insect Growth Regulator - Novaluron

Some insect growth regulators work by disrupting chitin synthesis in insects, as opposed to hormonal disruption of molting caused by methoprene. Novaluron, a new chitin synthesis inhibitor insect growth regulator, was recently tested against mosquitoes (Mulla, 2003; Su, 2003). Novaluron has been used as a chitin synthesis inhibitor for control of several agricultural and forestry pests. In this newest study, the product was tested for possible use against mosquitoes and was found to have exceptional long-term control activity against *Culex* mosquitoes and *Aedes aegypti*. Novaluron had consistently higher activity against *Ae. aegypti* larvae than either diflubenzuron or pyriproxyfen, other chitin inhibitors. Novaluron is not yet commercially available for mosquito control. The availability of new IGRs to mosquito control personnel would provide important tools for resistance management. However, insect control products from the same chemical class, when used repeatedly over a long period of time, often lead to build-up of resistance in the insect population.

7.5. Cinnamon Oils

Non-target insecticidal impacts and the development of resistance have led researchers to study plant oils as potential replacements for synthetic chemicals (Kim et al., 2001; Jang et al., 2002; Kim et al., 2002). In Taiwan, indigenous plants are increasingly being studied. Trees in the cinnamon family had been shown to have various preservative and insect-inhibitory effects. Cinnamon has at least eight essential oils in its leaves (an essential oil is a hydrophobic distillation product from plants, often important to carry fragrance or flavor). The oils can be grouped into five different chemical subsets. Tests of the larvicidal effects of these oils showed that two of these oils, cinnamaldehyde and cinnamaldehyde/cinnamyl were effective larvicides against 4th instar *Ae. aegypti*. The 24-hour LC_{50} values, that is, the concentration causing 50 percent mortality when applied for 24 hours, were 36 ppm for cinnamaldehyde and 44 ppm for cinnamaldehyde/cinnamyl. LC_{90} values were 79 ppm and 80 ppm, respectively. The active ingredients were tested for and extracted. All four had LC_{50} values of less than 50 ppm; with cinnamaldehyde extract, not the oil, being most effective, with a LC_{50} value of 29 ppm and a LC_{90} value of 48 ppm (Cheng et al., 2004). These oils may have non-target impacts, as they have been shown to have inhibitory effects on bacteria, termites, mildew, and fungi (Chang and Cheng, 2001). Costs, application means, and the stability of these chemicals in the environment have not been determined.

7.6. Adulticides

Control of adult mosquitoes is generally viewed as the last line of defense against these vectors. It may be the least efficient, as well, as adult mosquitoes are generally dispersed, and are associated with a medium, air, where control chemicals are difficult to concentrate so as to achieve the greatest effect. The term “adulticiding” is used to describe applying insecticide to kill adult mosquitoes, either while the insects are flying or resting in vegetation, in/on buildings, or in other sites of harborage (Meek, 1993). These applications can be made from the ground, via truck-mounted machines, or the air, via airplanes or helicopters, and are mostly applied using ultra-low volume (ULV) equipment. ULV is the application of small amounts of highly concentrated insecticide. The insecticide is applied using spray equipment that produces small droplets. For ground ULV applications the droplet size produced is generally in the 15 to 50 micron size range, depending on the chemical used and the specific label application recommendations. The actual amount of insecticide applied is typically in the range of 0.00117 to 0.076 pounds of active ingredient per acre, depending on the insecticide used (Cheminova Fyfanon® ULV label, Aventis Scourge® insecticide label).

Older mosquito spraying technology depended on “thermal fogging”, which aerosolized a petroleum/insecticide mix, creating a thick white fog. Thermal fogging is still legal in some states and may even be useful under certain conditions, such as fogging a yard, ball field, or small, thickly vegetated area where recreational activities are slated to occur later. ULV machines use less insecticide per acre, resulting in less environmental contamination, savings in insecticide costs, reduction in diluents, and reduced time in loading and transporting pesticides. Another advantage of ULV spraying is avoidance of dense fogs, such as those produced by thermal fogging.

There has been considerable evolution in pesticides used for adulticiding. At one time, DDT and other chlorinated hydrocarbons were used. Then, for decades, organophosphates were used almost exclusively. Now, most mosquito control districts use synthetic pyrethroids, which are chemically similar to naturally occurring pyrethrins (CDC, 2001). Pyrethroids are, generally, environmentally friendly and are reported to have extremely low mammalian toxicity. However, the widespread use of pyrethroids should not be construed to mean that organophosphates, such as malathion, are illegal or dangerous. In many places, malathion is still the insecticide of choice, due to pyrethroid resistance in the local mosquito population.

Only selected chemicals are approved for adult mosquito control in the US. Commonly used adulticides are listed below; a review of these chemicals can be found in Book 5 of the Literature Review.

- Organophosphate: Malathion. This product is often used in older thermal foggers, although there is a formulation for truck-mounted ULV machines.
- Organophosphate: Naled. This product is primarily applied by airplanes, although there is a ground-use label.
- Organophosphate: Chlorpyrifos. This product is not widely used in mosquito control.
- Botanical: Pyrethrins. Pyrethrin-based products, although environmentally friendly, are the most expensive.
- Synthetic Pyrethroid: Permethrin. Various formulations of permethrin, some with the synergist PBO, are the most widely used mosquito adulticides.
- Synthetic Pyrethroid: Sumithrin. This product is applied both by ground and airplane equipment.
- Synthetic Pyrethroid: Resmethrin. Resmethrin is applied by both ground and airplane equipment. It is a restricted use pesticide, which requires handlers to be certified in pesticide use by their state agriculture department.

Many of the above-mentioned adulticides are diluted with mineral oil. However, at least two products containing a synthetic pyrethroid can be diluted with water, Aqua Kontrol^{R} and Aqua-Reslin^{R}, although some controversy surrounds their use. Some mosquito control managers argue that water-based pyrethroids evaporate quicker in the air than oil-based products, although the manufacturers have data to the contrary.

7.6.1. Resistance Management

Development of insecticide resistance can result from over-exposure to pesticides in the same chemical class and/or exposure to sub-lethal doses (Wood and Mani, 1981). Resistance to some of the insecticides used for mosquito control has occurred periodically, resulting in a lack of pest control (Curtis and Pasteur, 1980). Currently, insecticides for adult mosquito control are from three classes – the botanicals (*e.g.*, pyrethrins), the organophosphates (*e.g.*, naled, malathion, chlopyrifos), and synthetic pyrethroids (*e.g.*, sumithrin, permethrin, resmethrin). Resistance to malathion, and to a lesser extent, to permethrin is already well-established. One study showed that Mississippi Delta *Anopheles quadrimaculatus,* species A of the complex, mosquitoes were 100 to 10,000 times more resistant to malathion than laboratory reared mosquitoes of the same species (Mallet, 1991). That same study also found significant resistance to permethrin. A scientific review of insecticide resistance issues worldwide revealed that pyrethroid resistance has been reported in two species of *Aedes*, ten species of *Anopheles*, and three species of *Culex* mosquitoes (Roberts and Andre, 1994). To properly manage resistance, insecticides with different modes of action are alternated, rotated, or mixed (Hemingway and Ranson, 2000; Rose, 2001; Knipling, 1979). Very few insecticides are registered for mosquito adulticiding, and overall, continued effective use of public health pesticides can be said to be in jeopardy (Knipling, 1979). Few new formulations are being discussed, and there is little economic incentive to develop them since mosquito and other vector control is a niche market. Widespread resistance to organophosphate mosquito adulticides, such as malathion, has been recognized for certain areas and species (see above). Development of pyrethroid resistance (also mentioned above), and recently reported resistance in the mosquito *Anopheles gambiae*, is particularly important, given the widespread use of pyrethroids for mosquito control (Rose, 2001). Although development of new mosquito control insecticides, particularly adulticides, is not expected to accelerate in the near future, integrated mosquito management (IMM) tools and techniques may allow for continued effective use of adulticides for selected control situations.

7.6.2. Automatic Misters for Residential Use

Various adaptations of a "misting system" installed around homes have been developed by, at least, three manufacturers recently. These systems are similar to sprinkler systems, except that they spray or fog an insecticide, usually a pyrethrin product, around the perimeter of the home for about one minute, two or more times a day. These systems are especially popular in Houston, Texas, and Minneapolis, Minnesota. One such system is called Mister Mosquito^{R} and utilizes a holding reservoir that not only stores the pyrethrum insecticide mix, but also regulates its release with an easy-to-use digital timer and high-pressure pump (Mister Mosquito Product Brochure, 2004). The brass misting nozzles are placed every 10-15 feet along the fence and/or eaves of a house. According to the manufacturer, the system is automated and maintenance free, and kills virtually all flying insects such as mosquitoes, wasps, bees, flies, gnats, and even spiders, roaches, and ants (Mister Mosquito Product Brochure, 2004). The disadvantages of this routine adulticiding system include, exposing the public to pesticides unnecessarily, buildup of mosquito resistance, and impacts on non-target organisms.

7.6.3. Sucrose-Based Mosquito Feeders

Harris County Mosquito Control (HCMC) in Houston, Texas, is conducting research on inexpensive sucrose-based mosquito “feeders” that deliver minute quantities of insecticide to adult mosquitoes (Parsons, 2003). If successful, these feeders theoretically could be placed in storm sewers to control *Culex* mosquitoes.

7.6.4. Novel Use of Thermal Fogging in Storm Drains

HCMC has the responsibility for prevention and control of mosquito-borne diseases throughout the county that includes the City of Houston. HCMC runs a large and effective program, even conducting operational research projects on novel mosquito control methods. HCMC controls *Culex* mosquitoes using ‘thermal fog’, not ULV, in those storm sewers where SLE and WNV have been found (Parsons, 2003). Treatments are administered by removing a manhole cover and directing the thermal fog into the manhole. Thermal fogging (see section 7.5 for more information) utilizes heat to convert pesticide in a petroleum diluent, such as diesel into a thick, white, smoke-like fog. The method was commonly used in mosquito control for many years, and can be an extremely effective means of delivering insecticide. It is still legal in many states. However, thermal fogging can be more expensive than ULV fogging and the thick fog creates a traffic hazard if it is aboveground. Because certain species of concern, especially *Culex spp*., appear to overwinter in storm drains and other stormwater control devices, this technique may be of considerable use in areas where WNV continues to cause epidemics (Enserink, 2002). Creation of traffic hazards due to fogging is not a concern in storm sewers, of course.

8. Home and Personal Control Measures

Chemical control of mosquitoes around the home may be accomplished with the use of repellents or space sprays. Repellents are commonly applied to skin or clothing to deter mosquito bites; space sprays are used to kill insects within relatively confined spaces. These products are discussed in Book 4, Part 3 of the Literature Review.

DEET is a commonly used repellent that appears in a number of commercial personal protection products. Oil of citronella is a common mosquito repellent that is typically used around the home. Oil of citronella is the active ingredient in many of the candles, torches, or coils, which may be burned to produce smoke that repels mosquitoes. These are useful outdoors only under windless conditions.

Repellents are much more effective when applied directly to skin or clothing, and DEET is unmatched at protection. A study by Fradin and Day (2002) testing landing rates in a laboratory demonstrated that DEET was considerably more effective than citronella or Avon Skin-so-soft^{TM}. A DEET formulation of 23.8 percent active ingredient repelled *Aedes* mosquitoes for a mean time of over 300 minutes, five hours, while the stronger Skin-so-soft formula worked for 20 minutes and the citronella for an average of 13 minutes. A children's formulation of DEET, 4.75 percent active ingredient, worked for a mean of 88 minutes. Wrist bands impregnated with these chemicals, no matter which formula was used, were ineffective at preventing mosquitoes from landing on and biting arms. A botanical product that showed some promise was the Bite-Blocker™ formulation.

Space sprays, small aerosol container products, may be used to kill mosquitoes present at the time of treatment. The major advantage of space treatment is immediate knockdown, quick application, and relatively small amounts of materials required for treatment. Space sprays are most effective indoors. Outdoors, the insecticide particles disperse rapidly and may not kill many mosquitoes. The major disadvantage of space spraying is that its effectiveness diminishes quickly.

Mosquitoes can be killed inside the house by using a household aerosol space spray containing synergized pyrethrum or synthetic pyrethroids (i.e., allethrin, resmethrin, etc.). Only insecticides labeled for flying insect management will have an effect. Labels indicate that best results are obtained if doors and windows are kept closed during spraying and for five to 10 minutes after spraying. Homeowners sometimes use hand-held foggers or fogging attachments on tractors or lawn mowers for temporary relief from flying mosquitoes. Pyrethrins or malathion can be fogged outdoors. Most mosquito professionals do not sanction such unlicensed, relatively uncontrolled use of pesticides.

9. Control Triggers

9.1. Correlation of Mosquito Numbers with Treatment Decisions

Data from surveillance can be correlated with reported disease prevalence or complaints of pest mosquitoes in an area (U. Florida and AMCA, 2004). But it is only after reviewing all of this information that the health officer or mosquito-control supervisor can make an intelligent decision as to the need for control measures and the type of control operations that will be most effective and economical.

Once a mosquito-control project is under way inspections are continued routinely and used to evaluate progress. Success or failure of a mosquito-control project cannot be measured in terms of the number of feet of ditches constructed or the number of gallons of insecticides used. While these statistics may be useful for some purposes, it is the actual density of mosquito populations that is most significant. If the density is reduced to a satisfactory level, routine surveys will reflect this reduction and document the accomplishment. On the other hand, if mosquito populations remain high, then the database results will spur intensified efforts to obtain the desired level of control.

The State of New Jersey has a web site wherein trap data collected from around the state are posted. In addition, these data are analyzed by medical entomologists, and trends, if any, are determined. These kinds of data sets allow the control professionals to place local surveillance data in context, and make informed decisions regarding the relative scope of an apparent mosquito problem (W. Crans, Rutgers University, personal communication, 2004).

Another means of putting data into context is, if possible, to conduct surveillance at some comparable, but untreated, breeding areas. These kinds of data may create a baseline data set possibly revealing the normal fluctuation of various species throughout the season. This could influence control measures, and also help to determine the efficacy of undertaken treatments.

9.2. Adulticiding

The decision to spray adulticides should be based upon established criteria, such as disease incidence, mosquito population density as measured by traps, or the number of complaints received.

Many people seek defined numerical triggers for the decision to adulticide. Developed trigger numbers vary. One program in Louisiana established triggers of 25 southern house mosquitoes or 25 Asian tiger mosquitoes in a gravid trap per 24 hours or 50 mosquitoes, each species, in a CDC trap. At a National Park in New York State, wildlife officials set a trigger for spraying at 50 female *Culex* mosquitoes in a CDC trap or 250 female *Oc. Sollicitans*, salt marsh mosquitoes, per trap, if West Nile virus has been reported near the park.

If complaint calls are used as a trigger, they should be correlated to mosquito counts for the most effective decision-making process. Factors, such as recent rainfall and the "age" of adult mosquitoes, should be considered in control decisions. For example, for heavy biting mosquito infestations, 50 "old" salt marsh mosquitoes caught in a light trap might not elicit as much concern as 20 "newly" emerged ones, because older mosquitoes tend to be less aggressive than nulliparous mosquitoes are. On the other hand, for WNV or EEE treatment decisions, older, previously-fed mosquitoes are of much greater concern as only parous mosquitoes can be infected with disease.

This conundrum, that parous mosquitoes tend to be fewer in numbers and less aggressive, but constitute the disease threat, is one reason why many mosquito professionals reject the notion of defined, numerical triggers for treatment decisions. Numerical triggers, whether trap data, landing rates, or complaints, will be biased towards treatment of nulliparous populations. However, especially where disease is the primary concern behind control, it is the less easily counted parous threat that constitutes the greater risk (Crans, 1976).

9.3. Treatment Algorithms

A recent report on mosquito control for county and city officials provides a decision matrix with guidelines for phased responses to West Nile virus surveillance data (ASTHO, 2004). The document defines various risk levels for WNV and then lists specific mosquito abatement measures. In addition, a document published by the World Health Organization (WHO) in 2002 describes the pros and cons of mosquito control and various factors to be considered in deciding when to treat and what to treat with (Najera, 2002). The WHO document contains a worldwide view of mosquito control practices, and algorithm-like charts of factors to consider in the decision-making process.

Table 9-1 is adapted from one of the figures contained in the WHO document (Najera, 2002). Table 9-2 lists the objectives of different mosquito control methods. Although Table 9-2 shows that adulticiding, fogging, has little expected effect on human biting, the document states that, "(during outdoor space spraying) [and] when applied at relatively short intervals, the resulting increase in adult mosquito mortality will, if required coverage can be achieved, rapidly reduce disease transmission."

Table 9-1 - Considerations for insecticide applications (Najera, 2002)

What to apply	Where to apply	How to apply	When to apply
Safety	Coverage requirements	Staff skills	Time required to cover target area
Efficacy	Best targeting	Staff training	Duration of effect
Cost-effectiveness		Equipment	Epidemiological requirements
Acceptability		Safety	
Availability			

Table 9-2 - Anticipated impacts of different types of vector control methods (Najera, 2002)

Method	Adult density	Adult survival	Human biting
Larval control			
Source reduction	+	--	--
Larvivorous fish	+	--	--
Larviciding	+	--	--
Control of human-vector contact			
Insecticide treated bed nets	+/--	+/--	+
Improved housing	--	--	+
Mosquito repellents	--	--	+
Adult mosquito control			
Indoor residual spraying	+	+	+
Space spraying (ULV or thermal fogging)	+	+/--	--

$^{+}$Reduction expected
$^{--}$No effect
$^{+/--}$Effect in some situations

9.4. Complaint Calls

The public can provide a valuable service by calling in mosquito problems. Complaint calls can be documented, even plotted on a city or county map, and can often help pinpoint large populations of mosquitoes, especially species such as the Asian tiger mosquito, *Aedes albopictus*, which do not readily enter light traps. In fact, one of the best ways to identify Asian tiger mosquito problems is through a well-run mosquito complaint documenting system. Treatment efforts can then be aimed at these "hot spots", when needed, and rather than treating the entire surrounding community.

In addition, complaint calls serve as a focusing factor for programs. It may be that the entire area of concern cannot be covered by traps due to manpower limitations, either to service the traps, or, more importantly, to analyze the collected data and determine the importance of the sampling. Complaint calls will allow undersampled areas to be recognized as having potential biting problems, which can then be investigated by program officers.

10. Program Effectiveness

Mosquito control programs need quality control systems in place to evaluate their effectiveness. For larviciding, a spot check of a certain percentage of treated breeding sites could be performed each month by counting mosquito larvae.

One way to monitor effectiveness of adulticiding is to set CDC light traps in zones slated for treatment a day before and a day after spraying. Alternatively, CDC traps could be set in the treated zones the day after adulticiding and an equal number set in a zone not treated on the same night (this would be an external control). This evaluative project would not have to be performed in all treatment zones, just randomly selected zones on randomly selected nights.

Data collected from this monitoring method would be useful in demonstrating that mosquito control efforts indeed work or if something is wrong with the control program (development of insecticide resistance, etc.). If CDC light trapping in an area that has been treated shows no effect *consistently* (not just once or twice) from the adulticiding, then something is wrong with the equipment, insecticides used, methods, etc.

New Jersey light trap data, from consistent sampling points, can serve much the same purpose. One issue with using such data is the potential confounding factor of natural variations. For this reason, wider networks of sampling data, such as supported in New Jersey, are extremely useful for placing local data in a wider context.

11. Mapping

Mapping of mosquito populations and treatments has always been a helpful tool to understand the overall trends associated with any program. The wider availability of more powerful mapping capabilities has enhanced the timeliness of such tools.

11.1. Private Aerial Mapping Services

Some private mosquito control companies offer a new aerial mosquito breeding survey service (Leahy, 2004a; ADAPCO, 2004b). Private contractors for mosquito control service are not new, but, apparently, contracting for specific "pieces" of the overall surveillance and control process is. This new mapping service is done by flying over the area in question, taking photos, and generating detailed maps of potential breeding areas for mosquito control personnel to use as they wish. The process defines, maps, and categorizes the total number of larval development sites, water sources suitable for mosquito larvae, and calculates the total acreage. Mapping of mosquito breeding areas is an essential component to an effective control program. These particular services, or similar ones, may help communities that do not have the aerial capability to develop accurate maps.

11.2. Habitat Mapping and Record Keeping

Habitat maps, records of mosquito populations and application methods used are valuable sources of information to the larvicide technician. A habitat map should show all known water areas, including artificial containers and floodwater areas.

The best way to conduct a habitat survey is by foot, inspecting each site for evidence of mosquito breeding. This insures a thorough inspection and allows the inspector to become familiar with the area. Both mosquito positive and mosquito negative sites should be recorded. Larviciding can then be confined to areas identified on the habitat maps.

Habitat maps can be verified during the first couple of larvicide applications. Newly discovered sites can subsequently be added. When the technician feels comfortable with the accuracy of the maps they can be entered into the County GIS system. During each larviciding trip, a set of these copies can be used as field maps. Notations concerning the day's activities can be recorded on each quadrant as the larvicide technician visits each site. Maps showing each week's activities can be kept on file for future reference on mosquito breeding trends.

12. Computer Software

12.1. GPS/GIS and Computer Modeling

Geographical Information System (GIS) maps have been used to reduce mosquito habitat in Rhode Island salt marshes (James-Pirri, 1996). Highly accurate maps of marsh features were generated. Marsh features such as tidal creeks, ditches, pools of water, and vegetation were marked with a Global Positioning System (GPS) unit. Additional information, such as the presence of fish or the number of mosquito larvae for any particular feature, can be stored in a data logger and uploaded to a GIS map. Permanent larval dipping stations can be established in the mapped marshes to record the abundance of mosquito larvae and to identify marsh areas that are mosquito-breeding habitats.

12.2. Habitat Mapping

Mosquito populations, and the diseases they carry, are influenced by a number of factors including temperature, rainfall, humidity, host abundance, and vegetation. Ecological and other environmental data can be combined with other data on a GIS map overlain on ultra-high resolution satellite images from commercial satellites. Satellites like Ikonos and Quickbird have a resolution as small as 80 cm (Barry, 2004). Regional data, such as temperature, rainfall, vegetation types, and soil moisture, can be obtained from medium-resolution satellite data (Landsat 7 or the MODIS sensor on NASA's Terra satellite). Scientists have been working on integrating all of this information into a computer simulation that runs on top of a digital map of the landscape (Barry, 2004). Sophisticated mathematical algorithms analyze the data and compute an estimate of the risk of a disease outbreak.

A recent NASA publication reports successful use of this mapping for disease prediction (Barry, 2004). A group from the University of Nevada and the Desert Research Institute were able to predict historical rates of deer-mouse infection by Sin Nombre virus, with up to 80 percent accuracy, based only on vegetation type and density, elevation and slope of the land, and hydrologic features, all derived from satellite data and GIS maps. A joint NASA Ames/University of California at Davis study achieved a 90 percent success rate in identifying which rice fields in central California would breed large numbers of mosquitoes and which would breed fewer, based on Landsat data. Another Ames project predicted 79 percent of the high-mosquito villages in the Chiapas region of Mexico based on landscape features seen in satellite images.

Mosquito abundance has been predicted by rainfall alone. For Africa, a computerized stochastic model and algorithm simulated the production of Rift Valley Fever mosquito vectors as a function of rainfall. Although it is still under development, it could allow vector abundance to be predicted without the arduous necessity of mosquito population sampling (Bicout, 2004).

12.3. Mosquito Management Software and Hardware

There are various versions of "mosquito management" or "vector management" computer software/hardware combinations which can be used to track spray truck paths, pesticide use, treatment histories, service calls, disease cases, complaints, and the like. One such program, called "Data Master II", integrates desktop computers, hand-held palm pilots, and a device attached to a ULV machine to track truck paths, pesticide use, and amounts sprayed (Leahy, 2004b). Detailed reports can be generated almost instantly. The Mosquito Mobile^{TM} enables mosquito control professionals to capture and analyze spatial and tabular data relating to mosquito breeding sites and treatment histories, as well as perform vector zone surveillance tasks, such as light trap and rain gauge monitoring (Bradshaw Consulting Services, 2004). The Monitor 3L^{TM} and Stab^{TM} are multipurpose variable control systems designed for vehicles applying mosquito control compounds, which can adjust flow rates proportionate to ground speed (ADAPCO, 2004c; ADAPCO, 2004d). The systems incorporate GPS tracking features and provide simultaneous reporting and recording of all pesticide application events. The system enables the user to “replay” a spray vehicle’s activity, even overlaid on detailed street maps. The manufacturer says that the Monitor 3L^{TM} will soon be capable of receiving and recording meteorological data pertinent to each spray application (ADAPCO, 2004c). A similar system, the Wingman GX^{TM}, is designed for aerial application of mosquito control products (ADAPCO, 2004e). This precision guidance and recording system receives real-time weather information, processes the USDA Forest Service AGDISP spray fate prediction software, and displays the optimization results to the pilot in real-time. According to the manufacturer, the pilot can see where the spray cloud is drifting, and, thus, is better able to deliver pesticide to its intended target (ADAPCO, 2004e).

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