

Pesticides and Public Health: Integrated Methods of Mosquito Management

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Pesticides have a role in public health as part of sustainable integrated mosquito management. Other components of such management include surveillance, source reduction or prevention, biological control, repellents, traps, and pesticide-resistance management. We assess the future use of mosquito control pesticides in view of niche markets, incentives for new product development, Environmental Protection Agency registration, the Food Quality Protection Act, and improved pest management strategies for mosquito control.

Vector-borne diseases (including a number that are mosquito-borne) are a major public health problem internationally. In the United States, dengue and malaria are frequently brought back from tropical and subtropical countries by travelers or migrant laborers, and autochthonous transmission of malaria and dengue occasionally occurs. In 1998, 90 confirmed cases of dengue and 1,611 cases of malaria were reported in the USA (1) and dengue transmission has occurred in Texas (2). Other vector-borne diseases continue to pose a public health threat. Even though the reported incidence of most of these diseases is low (in 1997, 10 cases of eastern equine encephalitis, 115 of LaCrosse, and 14 of St. Louis encephalitis [SLE]), occasional epidemics, e.g., of SLE (1,967 cases in 1975 and 247 cases in 1990, mostly in Florida [3]) have resulted in aerial applications of insecticides, primarily malathion. In addition, new vector-borne threats continue to emerge. In 1999, West Nile virus, an Old World flavivirus related to Saint Louis encephalitis virus, was first recorded in New York (4). The virus, which is transmitted by anthropophilic mosquitoes, caused a serious outbreak (62 cases, 7 deaths) and signaled the potential for similar outbreaks in the Western Hemisphere. Pesticides, which traditionally have been used in response to

epidemics, have a role in public health as part of sustainable integrated mosquito management for the prevention of vector-borne diseases. We assess the future use of pesticides in view of existing niche markets, incentives for new product development, Environment Protection Agency (EPA) registration, the Food Quality Protection Act (FQPA), and improved pest management strategies for mosquito control.

Sustainable Integrated Mosquito Management and Public Health

Mosquito control in the United States has evolved from reliance on insecticide application for control of adult mosquitoes (adulticide) to integrated pest management programs that include surveillance, source reduction, larvicide, and biological control, as well as public relations and education. The major principles of integrated mosquito management are available at a new Public Health Pest Control Manual internet website (5). Adulticides still play a vital role when flooding causes extreme numbers of nuisance mosquitoes or when outbreaks of diseases such as SLE occur.

Surveillance programs track diseases harbored by wild birds and sentinel chicken flocks; vector-borne pathogens in mosquitoes; adult and larval mosquitoes and larval habitats (by aerial photographs, topographic maps); mosquito traps; biting counts; and follow-up on complaints and reports by the public. When established mosquito larval and adult threshold populations are

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exceeded, control activities are initiated. Seasonal records are kept in concurrence with weather data to predict seasonal mosquito larval occurrence and adult flights.

Source reduction consists of elimination of larval habitats or rendering of such habitats unsuitable for larval development. Public education is an important component of source reduction. Many county or state mosquito control agencies have public school education programs that teach children what they and their families can do to prevent mosquito proliferation. Other forms of source reduction include open marsh water management, in which mosquito-producing areas on the marsh are connected by shallow ditches to deep water habitats to allow drainage or fish access; and rotational impoundment management, in which the marsh is minimally flooded during summer but is flap-gated to reintegrate impoundments to the estuary for the rest of the year.

Biological control includes use of many predators (dragonfly nymphs and other indigenous aquatic invertebrate predators such as *Toxorhynchites* spp. predacious mosquitoes) that eat larvae and pupae; however, the most commonly used biological control adjuncts are mosquito fish, *Gambusia affinis* and *G. holbrooki*. Naturally occurring *Fundulus* spp. and possibly *Rivulus* spp., killifish, also play an important role in mosquito control in open marsh water management and rotational impoundment management. Like many fish, mosquito fish are indiscriminate feeders that may eat tadpoles, zooplankton, aquatic insects, and other fish eggs and fry (6). However, since they are easily reared, they have become the most common supplemental biological control agent used in mosquito control. The entomopathogenic fungus, *Lagenidium giganteum*, has been registered for mosquito control by EPA under the trade name Liginex, but products have not become readily available. The pathogenic protozoon, *Nosema algerae*, has also not become available for technical reasons. Entomoparasitic nematodes such as *Romanomermis culicivorax* and *R. iyengari* are effective and do not require EPA registration but are not easily produced and have storage viability limitations. A predacious copepod, *Mesocyclops longisetus*, preys on mosquito larvae and is a candidate for local rearing with *Paramecium* spp. for food.

Mosquito traps (such as the New Jersey and the Centers for Disease Control and Prevention

designs) have been used for monitoring mosquito populations for years. New designs using mechanical control to capture adult mosquitoes have now become available. These designs use compressed carbon dioxide, burning propane, and octenol to attract mosquitoes and fans to control air flow. The new technology is expensive: these traps may cost well over \$1,000 each. Electric high-voltage insect traps ("bug zappers") with "black" or ultraviolet light sources do not provide satisfactory adult mosquito control and kill insects indiscriminately.

Pesticides

Pesticides used by state or local agencies to control nuisance or public health pests have warning labels and directions to minimize risks to human health and the environment. These pesticides are applied by public health employees who are specifically trained to follow proper safety precautions and directions for use. State or local mosquito control programs are funded by taxes and subject to public scrutiny. The environmental hazards precautionary statements on many mosquito insecticide labels state that insecticides are toxic to birds, fish, wildlife, aquatic invertebrates, and honeybees. Because of the low rates of application used to control mosquitoes and the special public health pest control training of most applicators, hazard to nontargeted organisms is limited. However, honeybees may be killed if exposed when foraging, so proper precautions are warranted. Human exposure in residential areas is also uncommon because of the very low application rates, ultra low-volume methods (ULV), treatment at night when people are indoors, pesticide applicator training, and public prenotification before application. Pesticide applicators who mix, load, and apply the concentrated insecticides use personal protective equipment to avoid exposure and closed systems to pump insecticides from storage to spray equipment.

The Federal Food Drug and Cosmetic Act (FFDCA) 21 USC 9§406 is the regulation that limits the quantity of any poisonous or deleterious substance added to food. A pesticide residue is the pesticide or its metabolites in or on raw agricultural commodities or processed food and feed. A tolerance is the maximum limit of a pesticide residue considered safe. Tolerances are relevant to adult mosquito control because wind drift may carry the pesticide over agricultural

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crops where residues subject to legal tolerance requirements may occur. Crop tolerances are listed in the Code of Federal Regulations (7).

Larvicides

Detection of large numbers of immature mosquitoes in areas where source reduction or biological control is not feasible may require larvicide treatment to prevent the emergence of

adult mosquitoes. Use of larvicides is less controversial than use of adulticides, although use of larvicides may lead to public concern about their effects on untargeted beneficial aquatic arthropods and vertebrates (Table).

Adulticides

Effective sustainable integrated mosquito management programs strive to prevent large

Table. Pesticides used for mosquito control in the United States

Name	Trade name	Formulation	Application	Advantage	Limitation
Temephos	Abate	G, EC	Larvae	Usually lowest cost	Nontarget effects, some resistance
Methoprene	Altosid	G, B, P, LC	Larvae	Residual briquets, nontarget safety	Cannot be certain of performance until too late to retreat
Oils	BVA, Golden Bear	Oil	Larvae, pupae	Acts on pupae	Oil film, subsurface larvae
Monomolecular film	Agnique	Liquid	Larvae, pupae	Acts on pupae	Subsurface larvae
<i>Bacillus thuringiensis israelensis</i> (Bti)	Aquabac, Bactimos, LarvX, Teknar, Dunks	WDG, AS, P,G,B	Larvae	Nontarget safety, Briquets control 30+ days	Short window of treatment opportunity. pupae
<i>Bacillus sphaericus</i> (Bs)	VectoLex	G, WDG	Larvae	Nontarget safety	Pupae, only works in fresh water
Malathion	Fyfanon, Atrapa, Prentox	ULV, thermal fog	Adults	Tolerances	OP, some resistance
Naled	Dibrom, Trumpet	ULV, EC, thermal fog	Adults	Tolerances	OP, corrosive
Fenthion	Batex	ULV	Adults	None specified	OP, Florida only, RUP, tolerances
Permethrin	Permanone, AquaResilin, Biomist, Mosquito-Beater	ULV, thermal fog, clothing treatment	Adults, clothing treatment for ticks and mosquitoes	Low vertebrate toxicity	None specified
Resmethrin	Scourge	ULV, thermal fog	Adults	Low vertebrate toxicity	RUP, no tolerance for residue on crops
Sumithrin	Anvil	ULV, thermal fog	Adults	Low vertebrate toxicity	No tolerance
Pyrethrins	Pyrenone, Pyronyl	ULV, EC	Adults, larvae	Natural pyrethrum, tolerances	May be costly

AS = Aqueous Suspension; B = Briquets; EC = Emulsifiable Concentrate; G = Granules; LC = Liquid Concentrate; P = Pellets; ULV = Ultra Low Volume; WDG = Water-Dispersible Granule; OP = Organophosphate insecticide; RUP = Restricted Use Product

flights or swarms of mosquitoes through all the measures described above, but heavy precipitation, flooding, high tides, environmental constraints, inaccessible larval habitats, missed breeding sites, human disease outbreaks, as well as budget shortfalls, absent employees, or equipment failures, may necessitate use of adulticides (Table). Some local mosquito control programs would use an integrated program if they had adequate resources, but may be so limited in funding and personnel that adulticiding trucks are the only means of mosquito intervention.

Effective adult mosquito control with insecticides requires small droplets that drift through areas where mosquitoes are flying. The droplets that impinge on mosquitoes provide the contact activity necessary to kill them. Large droplets that settle on the ground or vegetation without contacting mosquitoes waste material and may cause undesirable effects on nontargeted organisms. To achieve small droplets, special aerial and ground application ULV equipment is used. Insecticides are applied in a concentrated form or technical grade and at very low volumes such as 1 oz (29.6 mL) per acre. Typically, aerial applications produce spray droplets of 30 to 50 microns measured as mass median diameter, with $\leq 2.5\%$ of the droplets exceeding 100 microns. Ground ULV applicators produce droplets of 8 to 30 microns, with none > 50 microns mass median diameter. Large droplets of malathion, naled, and fenthion in excess of 50 to 100 microns can damage automotive or similar paint finishes.

Adulticide applications, particularly aerial applications and thermal fogging, are quite visible and contribute to public apprehension. Ground ULV application may be less alarming than aerial application but is not effective over large or inaccessible areas. Preferable air currents for ground applications are 3.2 kph to 12.9 kph and not in excess of 16.1 kph. Excessive wind and updrafts reduce control, but light wind is necessary for drifting spray droplets. With insecticide application by air using high-pressure pumps of 2,500 lbs psi, special nozzles, proper aerial application altitude and wind drift, mosquito control is achievable for several miles downwind with minimal spray deposit below the aircraft, as a result of improved atomization of the insecticide. This technology is being developed and needs validation under different

conditions with different mosquito species before it can be universally used. Thermal fogging, which was commonly used before ULV applications became prevalent, continues to be used in a few areas in the United States and is still widely used in other countries. The insecticide is diluted with petroleum oil and vaporized with heat into a dense, highly visible fog of very small uniform droplets, which allows tracking the plume downwind to target areas. Although this fog reduces visibility, it may also penetrate vegetation better than a ULV application. Small electric or propane thermal foggers are available for consumer use in retail stores at a cost of approximately \$60.00.

Adult mosquitoes are easily controlled with insecticides applied at extremely low rates. For example, malathion is applied at 3 fl oz per acre (219.8 mL/ha) for mosquitoes, while the rate for agriculture is as much as 16 fl oz per acre (1,172 mL/ha).

Insecticide Resistance

Vector resistance to certain larvicides and adulticides has occurred periodically. Failure of mosquito control indicating resistance must be verified by laboratory analysis or use of test kits because other factors (improper equipment calibration, dilution, timing and other application errors, off-specification products, climatic factors) can prevent insecticides from providing satisfactory control in the field. Resistance may occur between insecticides within a class or could be passed from immature to adult stages subject to the same insecticidal mode of action. Additionally, different species of mosquitoes may inherently vary in susceptibility to different larvicides and adulticides. Insecticides with different modes of action can be alternated to prevent resistance. Even though source reduction and use of predators such as larvivorous fish are also used for sustainable integrated mosquito management, only two chemical classes of adulticides (organophosphates and pyrethroids) with different modes of action are available. Biological controls (including birds and bats) may be present, but often not in sufficient numbers to provide satisfactory alternative control, particularly in coastal areas where salt-marsh mosquitoes are abundant or when human disease outbreaks occur. Therefore, sustained integrated mosquito management requires alternative use of different classes of insecticides, in conjunction

with resistance monitoring, source reduction, biological control, and public education.

Repellents

Insect repellents, primarily N,N-diethyl-metatoluamide (DEET), are used to prevent nuisance bites from mosquitoes (as well as ticks, biting flies, and mites) and may aid in lowering disease transmission from these pests. However, they should not be relied upon to prevent disease transmission, particularly where Lyme disease or encephalitis are endemic or malaria, yellow fever, or other vector-borne diseases are prevalent. Repellents, mosquito coils, and permethrin clothing treatment products are subject to EPA pesticide registration performance requirements (8). Information on safe use of repellents is located at the EPA Office of Pesticide Programs website (9). Citronella and its oil for mosquitoes and 30 other active ingredients are exempted from EPA pesticide registration (10). However, some of these products may not be efficacious.

Future of Public Health Pesticides

The past decade has seen a sharp rise in public apprehension concerning the use of pesticides, although state and federal regulations are well established for the assessment and mitigation of their human and environmental risks. Response to public concern over safety of pesticides prompted the FQPA, which includes provisions to protect availability of public health pesticides. However, public health pesticides are in jeopardy for the following reasons: In the United States, mosquito control programs are often for nuisance rather than disease vector control and not many insecticides are registered for this use. None of the mosquito adulticides commonly used were developed recently; their registrations are up to 44 years old. Mosquito control is only a niche market compared with agricultural pest control, which includes pesticides for use on corn, soybeans, and cotton, as well as the high-profit home, garden, and structural pest control markets. As pesticide companies have merged to form multinational conglomerates, the most profitable markets are those that drive corporate decisions. At present, it may require \$50 million or more to develop and register a new pesticide with EPA. Furthermore, several years of the patent life elapse before costs are recouped and profits accrue.

Vector control uses of existing pesticides, particularly adulticides, often follow agricultural registration and commercialization as a means of expanding sales into new markets. Performance data are not usually required for registration of agricultural pesticides, but these data are required for registration of public health pesticides. For mosquito control, these data are often obtained under an experimental use permit, which requires application to EPA, submission or reference to a portion of the pesticide registration requirements according to CFR 40 § 158 Data Requirements for Registration and Reporting (7,8). Testing for mosquito adulticides or larvicides is typically done by universities and mosquito control or abatement districts, although it may be done by companies or state or federal research organizations, such as the Department of Defense or the U.S. Department of Agriculture. In addition to defining dose rates, formulations, environmental variables, and effects that must be accommodated, testing under an experimental use permit provides a means of market introduction through user and customer experience, presentations at professional society meetings, and journal publications.

Pesticide marketing often involves distributors or dealers who specialize in the market if the manufacturers do not deal directly. Profit margins that add to price are required by distribution chains. Public agencies solicit competitive bids for pesticides, which squeeze margins further, thus affecting marketing incentives. Mosquito adulticides are used at very low rates of active ingredient per acre, which limits sales volumes and margins. Some seasons have few mosquitoes, so sales are low. Product liability also plays an important role in reducing incentives because of possible personal and class-action lawsuits or court injunctions against pesticides applied over populated areas.

The Federal Insecticide, Fungicide, and Rodenticide Act and FQPA

The Federal Insecticide, Fungicide, and Rodenticide Act 7 USC 136 and FFDCA were amended by the FQPA of 1996. Amendments pertinent to mosquito nuisance and vector control include the following: review of a pesticide's registration every 15 years; expediting minor use registrations; special provisions for public health pesticides; aggregate (all modes of

exposure from a single pesticide) and cumulative (all pesticides with the same mode of action) risk assessments; an additional safety factor of up to 10 X for children; collection of pesticide use information; and integrated pest management. Special provisions for public health pesticides include the following: risks and benefits considered separately from those of other pesticides; exemption from fees under certain circumstances; development and implementation of programs to control public health pests; Department of Health and Human Services (DHHS)-supported studies required for reregistration when needed; and appropriations of \$12 million for the first year after enactment and similar funding as needed in succeeding years to carry out public health pesticide provisions of the Act. The Act describes a consultation process between EPA and DHHS before any public health pesticide registration is suspended or canceled and allows additional time for submission of data. The first group of pesticides under review are the organophosphate cholinesterase inhibitors, including temephos, fenthion, naled, chlorpyrifos, and malathion. Should risk assessments result in detection of risk of concern to the Agency, cancellation or mitigations of use may follow, as exemplified by recent chlorpyrifos and diazinon use cancellations. Risk assessments may be based on data from acute and chronic toxicology and exposure studies, models that simulate exposure scenarios, reports of adverse incidents to humans and wildlife, extrapolation, maximum label use rate assumption, and worst-case exposure scenarios.

Even though the FQPA provisions were intended by Congress to ensure that existing public health pesticide uses are not lost without economically effective alternatives, the provisions may not be adequate. If FQPA results in cancellation of major agricultural uses of a pesticide that is also used in public health, it may become no longer profitable for the manufacturer to produce small quantities for mosquito control, thus ending production of the pesticide. Since adulticides used for mosquito control were registered decades ago, the data supporting their registrations may be insufficient to meet current requirements. The substantial cost involved in updating the data required for reregistration will have to be paid by pesticide registrants or the Federal government though the authorized and

appropriated funding in FQPA. Data to support reregistration done at public expense are not proprietary. Registrants need proprietary data to protect their market shares from generic pesticide competition from overseas manufacturers that can use public data to support their own registrations; therefore, they may not consider requesting public funds to pay for new data to support existing registrations. However, if generic safety studies applicable to several public health pesticides are required by EPA for all reregistrations, the data could be generated by a task force of registrants and county, state, and Federal public health agencies, which would then request public funding under the provisions of the Act.

Although the development of new mosquito insecticides, particularly adulticides, is not expected to accelerate in the near future, integrated pest management tools and techniques should improve as a result of FQPA funding and the need to control continued vector-borne disease outbreaks. Integrated pest management tools have strengths and weaknesses, and continued availability of adulticides is critical. Therefore, implementation of the public health pesticide provisions of FQPA must include substantial comparative risk-benefit analyses of the significance of vector-borne disease impacts versus potential human and environmental toxic effects of pesticides used to control public health pests, both in the USA and other countries affected by EPA pesticide regulatory decisions. Public information and legislative campaigns have also become necessary to preserve the availability and use of pesticides for disease vector control as FQPA has been implemented and with the concurrent spread of West Nile virus.

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