A Review of Studies Evaluating Insecticide Barrier Treatments for Mosquito Control From 1944 to 2018

Environmental Health Insights
Volume 13: 1–15

DOI: 10.1177/1178630219859004

Craig A Stoops[1], Whitney A Qualls[2], Thuy-Vi T Nguyen[3] and Stephanie L Richards[4]

[1]Mosquito Authority Laboratories, Green Cove Springs, FL, USA. [2]Zoonosis Control Branch, Texas Department of State Health Services, Austin, TX, USA. [3]Vector-Borne and Zoonotic Disease Team, Georgia Department of Public Health, Atlanta, GA, USA. [4]Department of Health Education and Promotion, East Carolina University, Greenville, NC, USA.

ABSTRACT

BACKGROUND AND PURPOSE: Barrier insecticide treatments have a long history in mosquito control programs but have been used more frequently in the United States in recent years for control of invasive "backyard" species (eg, *Aedes albopictus*) and increases in incidence of vector-borne diseases (eg, Zika).

METHODS: We reviewed the published literature for studies investigating barrier treatments for mosquito control during the last 74 years (1944-2018). We searched databases such as PubMed, Web of Science, and Google Scholar to retrieve worldwide literature on barrier treatments.

RESULTS: Forty-four studies that evaluated 20 active ingredients (AIs) and 21 formulated products against multiple mosquito species are included. Insecticides investigated for efficacy included organochlorines (dichlorodiphenyltrichloroethane [DDT], β-hexachlorocyclohexane [BHC]), organophosphates (malathion), and pyrethroids (bifenthrin, deltamethrin, permethrin, lambda-cyhalothrin) as AIs. Study design varied with multiple methods used to evaluate effectiveness of barrier treatments. Barrier treatments were effective at lowering mosquito populations although there was variation between studies and for different mosquito species. Factors other than AI, such as exposure to rainfall and application equipment used, also influenced control efficacy.

CONCLUSIONS: Many of the basic questions on the effectiveness of barrier insecticide applications have been answered, but several important details still must be investigated to improve precision and impact on vector-borne pathogen transmission. Recommendations are made to assist future evaluations of barrier treatments for mosquito control and to limit the potential development of insecticide resistance.

KEYWORDS: mosquito, barrier application, pyrethroid, permethrin, bifenthrin, DDT, *Aedes, Culex, Anopheles*

RECEIVED: May 9, 2019. **ACCEPTED:** May 15, 2019.

TYPE: Review

FUNDING: The author(s) received no financial support for the research, authorship, and/or publication of this article.

DECLARATION OF CONFLICTING INTERESTS: The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

CORRESPONDING AUTHOR: Craig A Stoops, Mosquito Authority Laboratories, 4048 J Louis Street, Green Cove Springs, FL 32054, USA. Email: craig.stoops@bugsbite.com

Introduction

Integrated mosquito management principles used in mosquito control programs (MCPs) include a variety of tools to target immature and adult stages to protect public health from potential vectors and reduce nuisance biting mosquitoes.[1] Mosquito population management emphasizes 4 core components: (1) personal protection against mosquito bites using repellents (eg, DEET), (2) environmental management (eg, container disposal, draining of ditches, water management), (3) larval control (ground and aerial application of larvicides), and (4) adult control (ground and aerial ultra-low volume [ULV] and barrier applications of adulticides).[1]

Methods to control adult mosquitoes over smaller areas (eg, residential backyards) include hand-held ULV treatments, thermal fogging, and/or the application of residual insecticides to vegetation, commonly referred to as "barrier sprays."[2] Barrier applications using backpack mist blowers are labor-intensive and may not be suitable for covering large areas; however, they can be used in certain situations for targeted control.[3] In the United States, an entire segment of the private pest control industry has emerged, focusing on barrier treatments to control mosquitoes in residential backyards based, in part, on (1) effectiveness of barrier treatments, (2) general budget reduction/dissolution of county/municipal mosquito programs in some regions, and (3) increased public awareness of mosquito-borne diseases.

Applications of insecticides using ULV or "cold fog" technologies are an important part of many MCPs. Insecticide droplets in ULV applications are most effective with a volume mean diameter between 5 and 25 μm, break down relatively quickly, and do not result in residuals on plants or other items that come into contact with the insecticide cloud. Conversely, barrier treatments are specifically designed to leave a residual coating on plants and have been defined as[4] "treatments for mosquito control where insecticidal products are applied onto localized areas of vegetation or natural/man made surfaces where mosquitoes may rest during the day." Perich et al[5] outlined the criteria that need to be met for a barrier application to be effective: (1) the species targeted must rest in vegetation before and/or after taking a blood meal, (2) a clear separation

between vegetation and human dwellings must exist, (3) oviposition sites must not be within the barrier, (4) insecticides with long residual times must be used, and (5) adult mosquitoes must make contact with the insecticide. These aspects of barrier treatments for mosquito control were recognized at the inception of vegetation treatments with insecticides in New Jersey in the 1930s and still are used by private and public MCPs.[6]

Here, we review published literature related to barrier treatments during the last 74 years (1944-2018). Databases such as PubMed, Web of Science, and Google Scholar were used to retrieve worldwide literature on barrier applications. Unpublished reports, master's theses, and doctoral dissertations were excluded here. Literature searches were conducted between January and December 2018. Terms used in the literature search included "barrier spray," "residual insecticide," "backpack sprayer," and "backyard mosquito control." Reference sections of primary articles were also reviewed for related publications. Table 1 provides information on the active ingredient (AI), method of application, mosquito species, and surveillance method used for all the papers cited in this review. Table 2 provides the trade name and AI for insecticides used in papers cited. Potential issues related to the relationship of barrier treatments to non-target organisms and insecticide resistance are briefly discussed.

Pyrethrum, Dichlorodiphenyltrichloroethane, and Organochlorines

Applying insecticides to vegetation to control mosquitoes was a technique recognized at the beginning of organized mosquito control. We review the use of pyrethrum, dichlorodiphenyltrichloroethane (DDT), β-hexachlorocyclohexane (BHC), lindane, and dieldrin as barrier treatments.

The idea that insecticides should be applied to vegetation where mosquitoes rest was conceived by Joseph M. Ginsburg of the New Jersey Agricultural Experiment Station in 1934 when he tested his newly developed New Jersey pyrethrum mosquito "larvicide" by applying it to vegetation to control adult mosquitoes in outdoor areas.[6] The "larvicide" consisted of an emulsion of 66% kerosene, 0.5% sodium lauryl sulfate, 0.07% pyrethrins, and "about" 34% water (the total exceeds 100%; however, these are the amounts reported in the paper).[6] If applications were made to all vegetation, structures, benches, and other surfaces, mosquito numbers post treatment were reduced.[6] It was recommended that the "larvicide" be applied to vegetation in small areas using knapsack sprayers or other small hand pump sprayers and, for large areas, power sprayers that could produce 14 kg/cm^2 of pressure. The larvicide was used until 1942 when the War Production Board prohibited the use of pyrethrums in preparation of the larvicide due to limited supplies available.[40]

During World War II, the US military embarked on a worldwide deployment where many troops were exposed to malaria and other mosquito-borne diseases that affected the fitness of the fighting force.[40] Because pyrethrum stocks were limited during the war, alternatives needed to be developed immediately.[6,40] During 1944, US Department of Agriculture (USDA) scientists conducted the first tests of DDT applied as a barrier application to control mosquitoes.[8] The study aimed to simulate conditions experienced by deployed troops in tropical areas and was carried out in heavily forested areas near Cocoa Beach, Florida. The barrier applications targeted pestiferous salt-marsh mosquito species (*Aedes taeniorhynchus* [Wiedemann] and *Ae sollicitans* [Walker]) with landing counts up to 200 landings/min. Vegetation was treated using 11.3 L hand compression sprayers with DDT mixed with No. 2 fuel oil and DDT aqueous emulsions in No. 2 fuel oil.[8] Application rates ranged from 5% to 20% DDT for the fuel oil solutions. Vegetation was treated in 2023 m^2 plots with the various solutions, including 1 experiment where vegetation was treated in 1 plot and the ground litter treated in another.[8] Percent mosquito reduction was calculated by measuring landings on the front legs of a human volunteer both inside barrier-treated areas and in untreated areas outside the barrier.[8] Landing rates were conducted 48 hours to 59 to 96 days following the treatment. Findings indicated that all DDT applications reduced landing counts of *Ae taeniorhynchus* and *Ae sollicitans*. Landing rate reductions (88%–99.8% reduction) were greatest in the 48 to 72 hours following the applications but showed reduction in mosquito numbers out to 96 days. The study showed that a 5% DDT aqueous emulsion performed best in reducing mosquito abundance.[8]

Another study[9] reported on tests of DDT dusts applied to vegetation for temporary control of mosquitoes in military encampments or bivouacs. DDT dusts ranging in concentration from 1% to 50% in talc were applied using hand rotary dusters to 1012 m^2 and up to 40 469 m^2 plots. Using a 50% concentration of DDT, landing counts of salt-marsh mosquitoes showed a 100% reduction 3 hours post application. Barrier applications using dusts, however, were abandoned because they were considered impractical to use when compared with liquids and aerosols. Others[7] continued testing DDT against salt-marsh mosquitoes in Florida using 19 to 114 L of DDT per 4047 m^2. Laboratory bioassays exposing *Anopheles quadrimaculatus* Say mosquitoes were exposed to treated leaves (5% DDT suspension) and showed 86% mortality up to 46 days post treatment. Reduction of *Ae sollicitans, Ae taeniorhynchus*, and *Psorophora* spp.[7] in treated "jungle" plots was 23% for pyrethrum, 26% for BHC, 41% for DDT solution, and 64% suspension for 53 days post application.[7]

Dichlorodiphenyltrichloroethane barrier treatments indicated that the flight range of the targeted mosquito species must be considered to help determine the appropriate height and depth of barrier treatments.[10] To test this, Ludvik[10] carried out a study in Alabama, where the formulation included 25% DDT, 63% xylene, 2% emulsifier, and 10% rosin (1:4 ratio; formulation:

Table 1. Summary of active ingredients and products evaluated in laboratory, semi-field, field barrier spray studies. Mosquito species, method of application, mosquito surveillance method, and results are also shown.

ACTIVE INGREDIENT	ASSOCIATED PRODUCT AND/OR MIXTURE	MOSQUITO SPECIES EVALUATED	METHOD OF APPLICATION	METHOD OF ASSESSMENT	FINDING	REFERENCE
Pyrethrum	Kerosene Piperonyl cyclohexenone	*Aedes taeniorhynchus* *Ae sollicitans* *Psorophora* spp.	Compression sprayer	Landing count	23% reduction at 53 d post treatment	Madden et al[7]
DDT	Fuel oil	*Ae taeniorhynchus* *Ae sollicitans*	Compression Sprayer	Landing count	88%-99% reduction 48-72 h post treatment	Madden et al[8]
DDT	Dust	*Ae taeniorhynchus* *Ae sollicitans*	Hand rotary dust sprayers	Landing count	100% reduction at 3 h post application	Madden et al[9]
DDT solution DDT suspension	Fuel oil Talc Water Piperonyl cyclohexenone	*Ae taeniorhynchus* *Ae sollicitans* *Psorophora* spp.	Compression Sprayer	Landing count	41% reduction at 53 d post treatment 64% reduction 53 d post treatment	Madden et al[7]
DDT	Fuel oil	*Ae taeniorhynchus* *Ae sollicitans*	Compression Sprayer	Leaf bioassay	86% mortality at 46 d post treatment	Madden et al[7]
DDT with xylene, emulsifier, and rosin	Water	*Anopheles quadrimaculatus*	Unknown	Mark, release, recapture	0.12% of mosquitoes recaptured within 8 wk post treatment	Ludvik[10]
DDT	Water	*Ae communis* *Ae fitchii* *Ae hexodontus*	Compression sprayer Mist blower	Landing counts	65%-100% control at 45 d post treatment	Hoffman and Lindquist[11]
DDT and emulsifier	Water	*Psorophora confinnis* *Ps discolor*	Airplane	New Jersey light traps	No satisfactory control	Quarterman et al[12]
DDT	Rosin Triton X-155 Xylene	*Ae taeniorhynchus* *Ae sollicitans*	Compression sprayer	Landing counts	6-9 wk of control	Bidlingmayer and Schoof[13]
BHC	Kerosene Piperonyl cyclohexenone	*Ae taeniorhynchus* *Ae sollicitans* *Psorophora* spp.	Compression Sprayer	Landing count	26% reduction at 53 d post treatment	Madden et al[7]
BHC	Triton X-155 Xylene	*Ae taeniorhynchus* *Ae sollicitans*	Compression sprayer	Landing counts	0-2 wk of control	Bidlingmayer and Schoof[13]
Methoxyclor	Water	*Ae stimulans* *Ae eudes* *Ae vexans*	Battery-operated pump	Leaf bioassay	3% mortality at 19 d post treatment	Helson and Surgeoner[14]
Lindane	Water	*Ae communis* *Ae fitchii* *Ae hexodontus*	Compression sprayer Mist blower	Landing counts	55%-93% reduction at 42 d	Hoffman and Lindquist[11]

(Continued)

Table 1. (Continued)

ACTIVE INGREDIENT	ASSOCIATED PRODUCT AND/ OR MIXTURE	MOSQUITO SPECIES EVALUATED	METHOD OF APPLICATION	METHOD OF ASSESSMENT	FINDING	REFERENCE
Lindane	Triton X-155 Xylene	*Ae taeniorhynchus* *Ae sollicitans*	Compression sprayer	Landing counts	0-2 wk of control	Bidlingmayer and Schoof[13]
Dieldrin	Triton X-155 Xylene	*Ae taeniorhynchus* *Ae sollicitans*	Compression sprayer	Landing counts	0-2 wk of control	Bidlingmayer and Schoof[13]
Chlorpyrifos	Water	*Ae stimulans* *Ae eudes* *Ae vexans*	Battery-operated pump sprayer	Leaf bioassay	5.7% mortality at 19 d post treatment	Helson and Surgeoner[14]
Iodofenfos	Water	*Ae stimulans* *Ae eudes* *Ae vexans*	Battery-operated pump sprayer	Leaf bioassay	0.5% mortality at 15 d post treatment	Helson and Surgeoner[14]
Malathion		*Ae taeniorhynchus* *Ae sollicitans*	Buffalo Turbine mist blower	Human landing counts	Control for 8 d post treatment	Anderson et al[15]
Malathion	Water	*Ae stimulans* *Ae eudes* *Ae vexans*	Battery-operated pump	Leaf bioassay	8.9% mortality at 15 d post treatment	Helson and Surgeoner[14]
Carbaryl	Water	*Ae stimulans* *Ae eudes* *Ae vexans*	Battery-operated pump	Leaf bioassay	60% mortality at 12 d post treatment	Helson and Surgeoner[14]
Permethrin (25%) Permethrin (1.25%)	EC EC	Multiple species	Compressed air sprayer	Human landing counts	Significant differences between treated vs untreated plots 2 d post treatment	Helson and Surgeoner[14]
Permethrin		*Ae taeniorhynchus* *Ae sollicitans*	Buffalo Turbine mist blower	Human landing counts	Control for 8 d post treatment	Anderson et al[15]
Permethrin	Water	*Ae stimulans* *Ae eudes* *Ae vexans*	Battery-operated pump	Leaf bioassay	7% mortality at 33 d post treatment	Helson and Surgeoner[14]
Permethrin and PBO	Water	*Ae albopictus* *Cx Quinquefasciatus*	RLFlowmaster 1025HD	Leaf bioassay	4.7% 3 wk post treatment (pooled species)	Cilek and Hallmon[16]
Permethrin PBO	Water	*Cx quinquefasciatus*	Twister XL backpack sprayer	Leaf bioassay	90% control up to 3 wk post treatment	Amoo et al[17]
Deltamethrin	Mineral oil	*An albimanus*	Aerial Micromist 900 Spray System	Light traps	Control for 8 d post treatment	Perich et al[5]

Table 1. (Continued)

ACTIVE INGREDIENT	ASSOCIATED PRODUCT AND/ OR MIXTURE	MOSQUITO SPECIES EVALUATED	METHOD OF APPLICATION	METHOD OF ASSESSMENT	FINDING	REFERENCE
Deltamethrin	Water	*Ae albopictus* *Ps columbiae*	Backpack mist blowers	CDC light traps baited with CO_2 Black oviposition cups	Applications every 21 d for 23 wk suppressed adult mosquito populations, but degree of effects depended on species and time of year.	Richards et al[18]
Deltamethrin	Water	*Ae albopictus* *Cx quinquefasciatus*	RLFlowmaster 1025HD	Leaf bioassay	99.8% 3 wk post treatment (pooled species)	Cilek and Hallmon[16]
Deltamethrin	Water	*Ae albopictus*	STIHL SR 200	Leaf bioassay	60 min exposure < 70% for 10 wk 5 min exposure 60 min knockdown < 40% up to week 6	McMillan et al[19]
Deltamethrin	Water	*Ae albopictus*	Hand compression Solo 423 backpack sprayer	Leaf bioassay	Mortality for 5 d post treatment	Bengoa et al[20]
Deltamethrin	Water	*Ae albopictus*	Hand compression Solo 423 backpack sprayer	Leaf bioassay	Mortality for 12 d post treatment	Bengoa et al[20]
Deltamethrin	Water	*Ae albopictus*	700 mL spray bottle	Leaf bioassay	>90% control up to 4 wk post treatment	Qualls et al[21]
Bifenthrin	Water	*Ae albopictus* *Cx pipiens*	STIHL SR 420	Human landing counts Sweep nets Ovitraps CDC gravid traps CDC light traps with CO_2	Control of *Ae albopictus* for up to 6 wk; no control for *Cx pipiens*	Trout et al[22]
Bifenthrin	Water	18 mosquito species	Modified pressure washer using Teejet nozzles	ABC light traps	91% reduction in mosquito abundance	Cilek[23]
Bifenthrin	Water	Field mosquito populations	Electrostatic applications	Encephalitis virus surveillance traps	Control up to 28 d	Britch et al[24]
Bifenthrin	Water	*Ae vigilax*	600L truck Mounted quick spray unit with a 3mm T400 nozzle	Light traps Human landing counts	Control up to 8 w post treatment	Hurst et al[25]

(Continued)

Table 1. (Continued)

ACTIVE INGREDIENT	ASSOCIATED PRODUCT AND/ OR MIXTURE	MOSQUITO SPECIES EVALUATED	METHOD OF APPLICATION	METHOD OF ASSESSMENT	FINDING	REFERENCE
Bifenthrin	Water	*Ae atlanticus* *Ae infirmatus* *Ps columbiae*	Flo-jet pump with a 40° flat fan nozzle	CDC light traps baited with octenol	Control up to 6 wk post treatment	Qualls et al[3]
Bifenthrin	Water	*Ae taeniorhynchus* *Ae sollicitans* *Ae atlanticus* *Ae infirmatus* *Cx nigripalpus* Culiseta *melanura* *Ps columbiae*	Hand compression sprayer and flo-jet pump with a 40° flat fan nozzle	Human landing counts CDC light traps baited with CO_2 Mosquito Magnet X trap with CO_2	Regardless of site or collection methods, control up to 3 wk post application	Qualls et al[26]
Bifenthrin	Water	*Ae* spp. *Cx* spp. *An* spp. *Cs* spp.	Backpack mist blower	CO_2-baited traps CO_2-baited BG Sentinel traps Larval surveillance	54%-74% reduction over the 16 wk post treatment period	VanDusen et al[27]
Bifenthrin	Water	Floodwater mosquitoes	3WC-30-4P American Long Ray; novel sprayer	CDC light traps	Mean reduction of 77% up to 4 wk post treatment	Fulcher et al[28]
Bifenthrin	Water	*Ae albopictus*	STIHL SR 420	BG Sentinel traps baited with BG-lures Black oviposition cups	Significant reduction in eggs and adults up to 4 wk post treatment	Bibbs et al[29]
Bifenthrin	Water	*Ae albopictus* *Ps columbiae*	Backpack mist blowers	CDC light traps baited with CO_2 Black oviposition cups	Applications every 21 d for 23 wk suppressed adult mosquito populations; but degree of effects depended on species and time of year.	Richards et al[18]
Bifenthrin	Water	*Ae albopictus*	STIHL SR 420	Leaf bioassay	50%-80% mortality over 8 wk	Trout et al[30]
Bifenthrin	Water	*Ae albopictus*	Compression sprayer	Leaf bioassay	77% mortality up to 35 d post treatment	Doyle et al[31]
Bifenthrin	Water	*Ae albopictus* *Cx quinquefasciatus*	Modified pressure washer fitted with Teejet nozzles	Leaf bioassay	>70% control at 4 wk post treatment	Cilek[23]
Bifenthrin	Water	*Ae aegypti*	STIHL SR 420	Leaf bioassay	70% (wax myrtle) and 40% knockdown (azalea) 4 wk following treatment	Allan et al[32]
Bifenthrin	Water	*Cx tarsalis*	STIHL SR 420	Leaf bioassay	>50% reduction for 28 d	Britch et al[24]

Table 1. (Continued)

ACTIVE INGREDIENT	ASSOCIATED PRODUCT AND/OR MIXTURE	MOSQUITO SPECIES EVALUATED	METHOD OF APPLICATION	METHOD OF ASSESSMENT	FINDING	REFERENCE
Bifenthrin	Water	*Ae albopictus*	STIHL 200	Leaf bioassay	>90% knockdown 60 min exposure for 2 wk 5 min exposure, 60 min knockdown > 80% for 2 wk	McMillan et al[19]
Bifenthrin	Water	*Ae albopictus*	700 mL spray bottle	Leaf bioassay	>90% reduction up to 4 wk post treatment	Qualls and Xue[21]
Bifenthrin	Water	*Ae albopictus*	700 mL spray bottle	Leaf bioassay	>90% reduction up to 4 wk post treatment	Qualls and Xue[21]
Bifenthrin	Water	*Ae aegypti*	3WC-30-4P American Long Ray Sprayer	Leaf bioassay	80% mortality at 2.7 m 51% mortality at 5.5 m	Fulcher et al[28]
Lambda-cyhalothrin	Water	*Ae albopictus* *Cx pipiens*	STIHL SR 420	Human landing counts Sweep nets Ovitraps CDC gravid traps CDC light traps with CO_2	Control of *Ae albopictus* for up to 6 wk; no reduction of *Cx pipiens*	Trout et al[30]
Lambda-cyhalothrin	Water	*Cx pipiens*	Power sprayer	CO_2-baited traps Gravid traps	8 wk reduction in *Cx pipiens* in tree canopies	Trout and Brown[22]
Lambda-cyhalothrin	Water	*Ae albopictus*	Marumaya MD6026 backpack sprayer	Human landing Rate	98% reduction 24 h after application/95% reduction after 9 wk	Li et al[33]
Lambda-cyhalothrin	Water	*Verrallina sp.*	STIHL SR 420	Sweep net	87%-100% reduction for up to 9 wk post treatment	Muzari et al[34]
Lambda-cyhalothrin	Water	*Ae albopictus*	STIHL SR 420	Leaf bioassay	40%-60% mortality over 8 wk	Trout et al[30]
Lambda-cyhalothrin	Water	*Ae albopictus*	STIHL SR 200	Leaf bioassay	60 min exposure >90% up to 8 wk 5 min exposure, 60 min knockdown > 75% to 8 wk	McMillan et al[19]
Lambda-cyhalothrin	Water	*Ae albopictus*	700 mL spray bottle	Leaf bioassay	>90% control up to 4 wk post treatment	Qualls and Xue[21]
Cypermethrin Tetramethrin PBO	Water	*Ae albopictus*	Elite 14S-300 SprayTeam Machine Tartaruga 300/3	Human landing counts	Control up to 14 d post treatment	Marini et al[35]

(Continued)

Table 1. (Continued)

ACTIVE INGREDIENT	ASSOCIATED PRODUCT AND/ OR MIXTURE	MOSQUITO SPECIES EVALUATED	METHOD OF APPLICATION	METHOD OF ASSESSMENT	FINDING	REFERENCE
Etofenprox Tetramethrin PBO	Water	*Ae albopictus*	Elite 14S-300 SprayTeam Machine Tartaruga 300/3	Human landing counts	Control up to 14 d post treatment	Marini et al[35]
Pyriproxyfen Pyriproxyfen and Lambda-cyhalothrin	Water Water	*Ae albopictus*	STIHL SR 420	BGS trap baited with BG lure	>70% control up to 4 wk post treatment	Unlu et al[36]
Pyriproxyfen	Water	*Ae albopictus*	STIHL SR 420	BGS trap baited with BG lure	No decrease in *Ae albopictus*	Suman et al[37]
d-phenothrin and PBO	Water	*Cx quinquefasciatus*	Twister XL backpack sprayer	Leaf bioassay	90% control up to 1 wk post treatment	Amoo et al[17]
Resmethrin	Water	*Cx quinquefasciatus*	Twister XL backpack sprayer	Leaf bioassay	90% control up to 1 wk post treatment	Amoo et al[17]
Cyfluthrin	Water	*Ae albopictus*	700 mL spray bottle	Leaf bioassay	>90% control up to 4 wk post treatment	Qualls and Xue[21]
Beta-cyfluthrin	Water	*Ae albopictus*	700 mL spray bottle	Leaf bioassay	>90% control up to 4 wk post treatment	Qualls and Xue[21]

Abbreviations: BHC, β-hexachlorocyclohexane; CDC, Centers for Disease Control and Prevention; DDT, dichlorodiphenyltrichloroethane; EC, emulsifiable concentrate; PBO, piperonyl butoxide.

Table 2. Registered name, AI, and referenced study of formulated products evaluated.

PRODUCT NAME	% AI	REFERENCE
Anvil 10 + 10	10% d-phenothrin 10% PBO	Amoo et al[17]
Aqua K-othrine	2.03 g/L Deltamethrin	Bengoa et al[20]
Aqua Reslin 20 + 20 EC	20% Permethrin 20% PBO	Amoo et al[17] Cilek and Hallmon[16]
Archer IGR	1.3% Pyriproxyfen	Unlu et al[36]
Bifen I/T	7.9% Bifenthrin	Richards et al[18] VanDusen et al[27]
Bifex AquaMax	100 g/L Bifenthrin	Hurst et al[25]
Bistar 80SC	80 g/L Bifenthrin	Standfast et al[38]
Black Flag	0.2% Resmethrin	Amoo et al[17]
Cy-Kick CS	6% Cyfluthrin	Qualls and Xue[21]
Demand CS	9.7% Lambda-cyhalothrin	Li et al[33] Muzari et al[34] McMillan et al[19] Qualls and Xue[21] Trout et al[30] Trout and Brown[22]
Duet	5% Sumithrin 1% Prallethrin 5% PBO	Gibson et al[39]
Etox 20/20 CE	20% Etofenprox 3% Tetramethrin 15% PBO	Marini et al[35]
K-othrine SC 25	2.56 Deltamethrin	Bengoa et al[20]
Masterline	7.9% Bifenthrin	Qualls and Xue[21]
Microsin	10% Cypermethrin 2% Tetramethrin 15% PBO	Marini et al[35]
NyGuard IGR	10% Pyriproxyfen	Suman et al[37]
Permanone EC	10% Permethrin	Cilek and Hallmon[16]
Suspend SC	4.75% Deltamethrin	Cilek and Hallmon[16] Qualls and Xue[21]
Suspend Polyzone	4.75% Deltamethrin	Richards et al[18] McMillan et al[19]
Talstar	7.9% Bifenthrin	Allan et al[32] Bibbs et al[29] Britch et al[24] Cilek[23] Doyle et al[31] Fulcher et al[28] McMillan et al[19] Qualls et al[3] Qualls et al[26] Trout et al[30]
Tempo SC Ultra	11.8% Beta-Cyfluthrin	Qualls and Xue[21]

Abbreviations: AI, active ingredient; CS, Capsule Suspension; PBO, piperonyl butoxide.

water). A strip of vegetation (3 m high × 15 m wide) was treated with approximately 1230 L/4047 m^2 (62 kg DDT/4047 m^2).[10] Following application, 5000 lab-reared *An quadrimaculatus* marked with fluorescent dye were released. Only 0.12% of these mosquitoes were recaptured within 8 weeks post treatment, leading investigators to conclude that the barrier treatment was successful.[10] A separate study[11] treated 2023 m^2 to 202 343 m^2 plots of vegetation with DDT and lindane to control snow melt mosquitoes such as *Ae communis* (DeGeer), *Ae fitchii* (Felt and Young), and *Ae hexodontus* Dyar in the Cascade mountains of Oregon. Both insecticides were diluted with water. Using 30 second landing counts, lindane (mixed at 1.4 kg/4047 m^2) provided a similar level of control as DDT (mixed at 1.8 kg/4047 m^2). Quarterman et al[12] applied 1.4 kg DDT per 3.8 L of water with 2.5% emulsifier by airplane to a 122 m swath of vegetation to control rice field mosquitoes. New Jersey light traps were placed inside and outside the barrier. Satisfactory control was not achieved as 7000 to 10 000 mosquitoes were collected in the traps during the first 4 nights following application.

It was reported that treating outbuildings and vegetation to a radius of 30.5 m from a house with 2.3 kg/4047 m^2 DDT resulted in 6 weeks of control and 4.5 kg/4047 m^2 DDT resulted in 9 weeks of control of *Ae sollicitans* and *Ae taeniorhynchus*.[13] In concurrent tests of BHC, lindane, and dieldrin in these residential settings, control lasted only from 0 to 2 weeks.[13] Under high mosquito pressure, DDT treatments were also considered ineffective after 2 weeks.

Dichlorodiphenyltrichloroethane continued to be used in many MCPs over the next several years but before insecticide resistance and environmental impacts of insecticide misuse were realized. Dichlorodiphenyltrichloroethane began to be phased out and other chemicals such as BHC, dichlorodiphenyldichloroethane (DDD), lindane, dieldrin, heptachlor, and aldrin were incorporated into MCPs.[41,42] Organophosphate insecticides were also being used, and by 1954, the use of malathion was widespread for barrier vegetation applications to control mosquitoes in California.[43] As organophosphates were being incorporated, reports of resistance in mosquito populations to DDT and other organochlorines increased, and focus shifted to the newly developed and marketed synthetic pyrethroids to control both vector and pest mosquitoes. No peer-reviewed studies that investigated an organophosphate insecticide alone were found; however, Helson and Surgeoner[14] reported the efficacy of chlorpyrifos and iodofenfos in laboratory bioassays and Anderson et al[15] reported the efficacy malathion in the field. The comparisons are reported with the pyrethroids to emphasize the differences in efficacy.

Pyrethroids

The first synthetic pyrethroid, allethrin, was discovered in 1949 by chemists at the USDA in Beltsville, Maryland.[44] In 1962, scientists at the Rothamsted Experimental Station in the United

Kingdom, led by Dr Michael Elliot, developed resmethrin.[45] The group at Rothamsted in the 1970s discovered permethrin, cypermethrin, and deltamethrin, with Sumitomo discovering fenvalerate about the same time.[45] With the banning of DDT in the United States in 1972 and the loss of many organochlorines for public health uses, pyrethroids are the main insecticides currently used to control mosquitoes. Government and private pest control companies rely almost exclusively on pyrethroids to control adult mosquitoes through ULV and/or barrier applications. We report results on 12 synthetic pyrethroid AIs used: bifenthrin, cyfluthrin, cypermethrin, d-phenothrin, deltamethrin, fenvalerate, lambda-cyhalothrin, permethrin, prallethrin, resmethrin, sumithrin, and tetramethrin.

Bioassays and Semi-Field Studies

Bioassays provide evidence of AI efficacy, including behavior changes and lethality to different mosquito populations under controlled conditions. These data are important in determining biological activity of an AI and large data sets can be generated across AIs, mosquito populations/species, and their susceptibility/resistance profiles for each tested AI. Semi-field studies allow investigators to obtain data on the effectiveness of an insecticide under more controlled conditions than a field study that may be subject to variable weather conditions and mosquito occurrence and abundance. Caution is advised when interpreting laboratory results due to the different methods that may be used between laboratories. Many of the studies included in this review reported results of both laboratory bioassays and field studies with a few including semi-field studies. Bioassays and semi-field studies were separated from field studies to highlight the results of these bioassays and so methods and results can be compared without being confused with studies in the field. Studies are presented in chronological order to highlight the changes in methods and chemicals over time.

Five emulsifiable concentrate (EC) insecticides including 25% methoxyclor, 10% chlorpyrifos, 20% iodofenfos, 50% malathion, and 1.25% permethrin and 1 wettable powder, 50% carbaryl, were evaluated as residual applications to vegetation.[14] The study also compared 4 formulations of permethrin: 1.25% EC, 25% EC, 25% wettable powder, and 0.25% oil solution. Additional pyrethroids including 30% fenvalerate EC and 40% cypermethrin EC were compared with 1.25% permethrin. Plots (2 m × 2 m) of smooth brome grass (*Bromus inermis*) were treated with a battery-operated pump sprayer with each insecticide at 0.25 g AI/m^2. Field-collected mosquitoes, including *Ae stimulans* (Walker), *Ae eudes* Howard, Dyar and Knab, and *Ae vexans* (Meigen), from these treated sites were placed in plastic containers in the laboratory and mortality recorded up to 24 hours.[14] When *Ae eudes* and *Ae vexans* were exposed to the brome grass immediately (day 0) after treatment, all insecticides produced 100% mortality except for iodofenphos, which showed only 64% mortality. At day 15, mosquitoes exposed to permethrin-treated brome grass had a 97% mortality with that of malathion 6%, iodofenfos 0.5%, methoxychlor 3%, and carbaryl 0%. Permethrin had the longest effective residual time, 7% mortality at day 33, with all other chemicals with no mortality by day 26. In the comparison of the permethrin formulations, the oil formulation resulted in the highest mosquito mortality (14%) of *Ae eudes* and *Ae vexans* at 9 days after mosquitoes were collected from the field. And in the comparison of various dosages of 1.25% permethrin, the highest dose 0.2 g AI/m^2 had the longest residual effect (5% to 40 days mortality). When permethrin, fenvalerate, and cypermethrin were compared, in both the 0.00625 and 0.01 g AI/m^2 groups, cypermethrin had the longest residual effect: 14% mortality at 16 days, 4% mortality at 21 days.

A semi-field study in large screened enclosures looked at the residual effectiveness of Aqua Reslin 20 + 20 EC (20% permethrin, 20% piperonyl butoxide [PBO]), Permanone EC (10% permethrin), and Suspend SC (4.75% deltamethrin) against *Ae albopictus* and *Culex quinquefasciatus* Say on potted wax myrtle (*Morella cerifera*).[16] Plants were treated using a RL Flowmaster, Model 1025 HD hand pump. Suspend SC provided the best control over a 4-week period, followed by Permanone EC and Aqua Reslin 20 + 20 EC. The reported variation in efficacy among products was likely due to formulation type and new leaf growth on plants providing untreated harborages for the mosquitoes. Bioassays were conducted to test the effectiveness of Talstar One (bifenthrin 7.9%) and Demand Capsule Suspension (CS) (lambda-cyhalothrin 9.7%) against *Ae albopictus*.[30] In the same study, adult female *Ae albopictus* were exposed to deciduous tree leaves treated in the field using a STIHL SR 420 backpack sprayer with bifenthrin or lambda-cyhalothrin or were untreated. No difference in mortality was observed in mosquitoes exposed to either insecticide, but mortality was significantly higher in treated compared with untreated leaves at 6 weeks post treatment.

In laboratory bioassays, *Cx quinquefasciatus* was exposed to leaves from plants treated in the field using a Twister XL backpack sprayer with either AquaReslin (20% permethrin, 20% PBO), Anvil 10 + 10 ULV (10% d-phenothrin, 10% PBO), or Black Flag (0.2% resmethrin).[17] The same study showed 90% mosquito mortality for permethrin for up to 1 week post application.[17] Leaves treated with AquaReslin (20% permethrin, 20% PBO) resulted in mortality up to 3 weeks post application. In laboratory bioassays of leaves taken from plants treated with Talstar One (7.9% bifenthrin) using a modified pressure washer fitted with Teejet nozzles, >70% mortality was recorded in both *Cx quinquefasciatus* and *Ae albopictus* for up to 4 weeks.[23]

Laboratory behavior experiments[46] found that *Cx quinquefasciatus* spent more time resting on surfaces treated with bifenthrin, lambda-cyhalothrin, and deltamethrin compared with *Ae aegypti* and *An quadrimaculatus*. Bifenthrin-treated papers had the fastest knockdown against the 3 species tested. The authors suggest "locomotory stimulant" replace the term "excito-repellency" when describing the action of a chemical, as it more accurately describes how insecticide-treated surfaces influence mosquito behavior.[46]

In a semi-field study,[32] potted wax myrtle and azalea (*Rhododendron simsii*) plants were treated with Talstar One (7.9% bifenthrin) using a STIHL SR 420 backpack sprayer or an Electrolon BP 2.5 electrostatic sprayer. Following treatment, plants were separated into groups and were placed in full sun or under a tree canopy to determine the impact of sunlight or moved into a greenhouse and exposed to simulated rainfall with plants receiving 24 cm of "rainfall." Bioassays exposed *Ae aegypti* to single Talstar One treated leaves for 1, 4, and 24 hours. Differences in % knockdown were found between treatment methods, both plant species, and exposure to rainfall and/or sun. For example, at the 1-hour exposure period at week 4 for wax myrtle leaves treated with a backpack sprayer, % knockdown was <70% for leaves not exposed to rainfall and <40% for leaves exposed to rainfall. At week 4 and 1-hour exposure for azalea leaves treated with the backpack sprayer, % knockdown was <40% for leaves not exposed to rain and <20% for leaves exposed to rain. Regardless of treatment method or plant species, rainfall was the most important factor in removing bifenthrin from the leaf surface and decreasing % knockdown.[32] In laboratory bioassays,[24] it was determined that desert vegetation (eg, *Tamarax chinensis*) treated with Talstar (bifenthrin 7.9%) using a STIHL SR 420 caused more than 50% mortality of *Cx tarsalis* Coquillet for 28 days. Doyle et al[31] found quick knockdown of *Ae albopictus* with Talstar One (bifenthrin 7.9%) applied by a hand compression sprayer in bioassays of various plant species in Florida. Plant species affected knockdown, with a variety of *Rhododendron* showing the longest residual efficacy and leaf shape and waxiness of the plant surface possibly playing an important role in the effectiveness of the residual application.

The effect of insecticide-treated vegetation on *Ae albopictus* was reported[20] using K-othrine SC 25 (deltamethrin 2.56%) and Aqua K-othrine (deltamethrin 2.03%) in Spain. Applications to vegetation in plots were made using a hand compression Solo 423 backpack sprayer and mosquitoes were exposed to treated leaves in the laboratory. Compared with studies in the United States with deltamethrin, the mortality period was shorter, with mortality for Aqua K-othrine-treated plants out to 12 days, and 5 days for K-othrine-treated plants.[20] In semi-field cages,[21] male and female *Ae albopictus* were exposed to wax myrtle plants treated with 1 of 6 products: Cy-kick CS (6% Cyfluthrin), Masterline (7.9% bifenthrin), Tempo SC Ultra (11.8% β-cyfluthrin), Demand CS (9.7% lambda-cyhalothrin), Suspend SC (4.75% deltamethrin), and Talstar P (7.9% bifenthrin). Leaves were treated to maximum label rates of each insecticide using a 700 mL spray bottle. Mortality was assessed weekly with >90% mortality for 4 weeks against *Ae albopictus* for all 6 products. Others[34] reported bioassays of leaves treated in the field with Demand (25 g/L lambda-cyhalothrin) using a STIHL SR 420 backpack sprayer against *Ae aegypti*. Treated leaves caused 100% mortality of exposed *Ae aegypti* at 5 weeks post application and 96% mortality at 14 weeks.

Two different machines were evaluated for barrier applications, the Elite 14S-300 SprayTeam Machine and the Tartaruga 300/3 with 2 different insecticides, Microsin (cypermethrin 10%, tetramethrin 2%, PBO 15%) and Etox 20/20 CE (etofenprox 20%, tetramethrin 3%, PBO 15%).[35] After exposure to the 2 insecticides, mosquitoes showed equal mortality after day 1 (>90%), with Etox-exposed mosquitoes having a higher mortality after 7 days (78%) versus Microsin (65%). However, in the same study, by day 14 post treatment, mosquitoes exposed to either insecticide showed nearly equal mortality (Etox 50% and Microsin 55%).

Fulcher et al[28] conducted bioassays exposing *Ae aegypti* to leaves treated with Talstar P (7.9% bifenthrin) applied in the field with a mist sprayer (3WC-30-4P). The sprayer adequately covered foliage and mean mosquito mortality in bioassays against *Ae aegypti* indicated lethal coverage in vegetation treated out to 12 m. The greatest mean mortality was 51% at 5.5 m and 80% at 2.7 m, indicating that plants closer to the applicator might receive higher levels of formulated product.[28]

Demand CS (9.7% lambda-cyhalothrin), Talstar P (7.9% bifenthrin), and Suspend Polyzone (deltamethrin 4.75%) were evaluated against *Ae albopictus* in laboratory bioassays.[19] Insecticide was applied using a STIHL SR 200 backpack sprayer. Two exposure times were evaluated to determine the validity of the standard 60 minutes and 24 hour exposure times. Mosquitoes were exposed at the standard times in 1 experiment and were exposed to the treated leaves only for 5 minutes before being transferred to a clean vial in a second experiment. In both experiments, leaves were collected from each plant species once a week for 12 weeks. In the standard 60-minute exposure time, knockdown for lambda-cyhalothrin was >90% up to week 8, whereas bifenthrin knockdown was only >90% up to week 2 and for deltamethrin was not >70% for 10 weeks. No significant difference in knockdown was found between AIs for the 24-hour exposure group. For the 5-minute exposure group, knockdown at 60 minutes was >75% until week 8 for lambda-cyhalothrin, >80% for 2 weeks for bifenthrin, and was never >40% for deltamethrin. The 5-minute exposure, 24-hour mortality for lambda-cyhalothrin was >60% up to week 8, mortality was >80% up to week 2 for bifenthrin, and <40% for deltamethrin up to week 6.

Field Testing

The machines used to apply a barrier application are critical to the effectiveness of the application against mosquitoes. Also, comparing different methods of application (barrier vs ULV) is important in understanding when to choose a method and its impact on different mosquito populations and species. For example, conventional and electrostatic sprayers showed similar efficacy in barrier insecticide applications[4] with the best deposition/residual coverage from equipment having the highest air velocity at the nozzle and the largest droplet sizes. The overall mean deposition of AIs on plant surfaces for all sprayers tested ranged from 8.8 to 20.8 ng/cm^2. Leaves treated with

STIHL backpack sprayers showed significantly greater deposition on the top versus the bottom of leaves and peak deposition occurred 1 m into the vegetation.[4] Farooq et al[47] found that electrostatic sprayers were not effective for barrier spray applications. In the same study, droplets were measured on water-sensitive cards at varying heights and depths to determine spray coverage. Droplet coverage was significantly affected by sprayer type, card depth, and vegetation height. Droplets from the electrostatic sprayers seemed to rapidly descend to the ground, while traditional sprayers had overall better droplet penetration into vegetation (eg, 1-3 m for the STIHL SR 420). Conversely, in a study of barrier treatments in the desert of Coachella Valley, California, vegetation treated with Talstar (bifenthrin 7.9%) using electrostatic applications reduced mosquito populations slightly more than the traditional backpack applications, but the difference was not statistically significant.[24]

To compare the impact of using a space spraying strategy versus a barrier spray in residential backyards, results were reported from testing a thermal fog machine (LongRay TS-35A) versus a barrier application using a Birchmeier REC 15.[39] Treatment of the property with the LongRay TS-35A using DUET (Sumithrin 5%, Prallethrin 1%, PBO 5%) resulted in a 1-week reduction of mosquitoes. The barrier application of Talstar P (bifenthrin 7.9%) using the Birchmeier REC 15 was made to vegetation at the same property once the landing counts returned to pre-thermal fog numbers.[39] The barrier application suppressed mosquitoes significantly for 3 weeks post application. Using Centers for Disease Control and Prevention (CDC) light traps baited with octenol, the impact of barrier applications and ULV applications on floodwater mosquitoes such as *Ae atlanticus* Dyar and Knab, *Ae infirmatus* Dyar and Knab, and *Psorophora columbiae* Dyar and Knab was evaluated in northern Florida.[3] Barrier applications of Talstar P (bifenthrin 7.9%) significantly reduced the number of *Ae atlanticus* and *An crucians* Weidemann for 6 weeks. The area treated with the barrier application alone had significantly fewer requests for treatment from the Anastasia Mosquito Control District (AMCD), Florida, during the study, compared with the area that received only the ULV treatment alone. This was the first time that barrier sprays were shown to significantly decrease populations of these important pest mosquito species.[3]

Permethrin

In a trial in Guelph, Ontario, 25% permethrin EC and 1.25% permethrin EC were applied using a compressed air sprayer to backyards and a 10 to 15 m horizontal swath of the surrounding woods.[14] Permethrin was applied at a rate of 0.7 g AI/100 m^2. Human landing counts were used to evaluate the effectiveness of the applications and mosquito species were not reported. Differences in landing counts between treated and untreated control plots were significant up to 2 days post treatment. The authors reported that fewer mosquitoes (although not statistically significant) were collected in treated versus untreated plots until 7 days post treatment.[14]

Barrier treatments in North Carolina, using permethrin (10% EC, 30 mg AI/m^2) and malathion (57% EC, 170 mg AI/m^2) were carried out using a Buffalo Turbine mist blower.[15] Human landing counts were used to evaluate mosquito abundance pre- and post treatment. Landing activity decreased 80% to 90% at 1 and 24 hours sampling periods in both the areas treated with permethrin and malathion, compared with the untreated area. Landing counts of *Ae sollicitans* and *Ae taeniorhynchus* were significantly lower for vegetation treated with permethrin up to 8 days post treatment. Mosquito populations, however, returned to pre-treatment abundance 48 hours after malathion application.[15]

Deltamethrin

An aerial treatment of deltamethrin (1 mg AI/m^2) mixed with mineral oil was applied to foliage surrounding 2 cities in the Dominican Republic using a Micromist 900 Spray System.[5] Light traps indicated mosquito suppression for up to 8 days post treatment. Investigators pointed out that mineral oil does not affect residual persistence due to the nonpolar nature of pyrethroids. However, the use of natural oils, such as soybean oil was suggested as a method to improve persistence of the AI on leaves because the oils may bind to their waxy coating.[5]

Properties treated with Suspend Polyzone (deltamethrin 4.75%) by a private mosquito control company showed a fewer mosquitoes in CDC light traps baited with dry ice in Polyzone treated properties (5.5 and 4.6 per trap night) than in untreated control properties (6.6 and 8.0 per trap night).[18] Eggs of *Ae albopictus* collected in Polyzone treated properties were lower (37 and 34 eggs per trap) than in the untreated control properties (49 and 44 eggs per trap); however, this difference was not significant. The same study showed no significant difference in the overall number of mosquitoes collected between bifenthrin- and deltamethrin-treated properties and *Psorophora columbiae* was the only species significantly reduced in treated versus untreated properties.

Lambda-Cyhalothrin

In Lexington, Kentucky, 2 studies were carried out looking at the impact of barrier treatments using a STIHL SR 420 backpack sprayer and Demand CS (lambda-cyhalothrin 9.7%). Mosquito populations were measured using a variety of sampling methods such as human landing collections, sweep nets, ovitraps, CDC gravid traps, and CDC light traps baited with CO_2. Applications of Demand CS showed 6 weeks of reduced populations and an 89% reduction in *Ae albopictus* populations versus controls, but did not show an impact on *Cx pipiens* L. populations.[30] Also in Lexington, Kentucky, to determine if barrier applications to upper canopy versus lower canopy had a greater effect on *Cx pipiens*, Trout and Brown[22] evaluated

Demand CS (lambda-cyhalothrin, 9.7%) and measured mosquito populations with CO_2-baited traps hung at canopy and ground level. Gravid traps were also used for the evaluation at ground level. When mosquitoes were trapped using CDC light traps baited with CO_2, an 8-week reduction of *Culex* spp. was reported in the treated canopies compared with no significant reduction in the untreated canopy. For the gravid trap collections, *Culex* spp. abundance in treated versus untreated sites, the authors felt that gravid females seeking oviposition sites might not have contacted the insecticide-treated vegetation, hence decreasing its effectiveness.

Demand CS (lambda-cyhalothrin 9.7%) was applied to vegetation and resting areas to control *Ae albopictus* in a residential yard in Beijing, China.[33] The insecticide was applied using a Marumaya MD6026 backpack sprayer and mosquito numbers were measured using human landing rates. Mosquito landing rates in the treated yard were reduced by 98% compared with landing rates in the untreated yard the day after the application and 95% at 9 weeks post application.[33]

In North Queensland Australia, Muzari et al[34] reported that applications of Demand (25 g lambda-cyhalothrin/L) using a STIHL 420 backpack sprayer resulted in 87% to 100% control of mosquitoes collected with sweep nets in treated versus untreated controls over the first 9 weeks. These treatments significantly reduced forest dwelling *Verrallina* spp. such as *Verrallina lineata* Taylor and *Verrallina funerea* Theobold.[34]

In New Jersey, the insect growth regulator (IGR), pyriproxyfen (Archer IGR, pyriproxyfen 1.3%) was added to lambda-cyhalothrin (Demand CS, lambda-cyhalothrin, 9.7%)[36] to determine if adding IGR improved mosquito control in barrier applications. No significant decrease in the number of collected mosquitoes was found between properties that had lambda-cyhalothrin + pyriproxyfen versus properties treated with lambda-cyhalothrin alone. The same study also treated properties with pyriproxyfen alone and found no significant decrease in mosquito numbers collected compared with the untreated controls. These studies support another study[29] that also reported in New Jersey that area-wide treatments of vegetated plots using a STIHL SR 420 to apply NyGuard IGR Concentrate (10% pyriproxyfen) did not decrease the number of *Ae albopictus* collected in Biogents (BG) Sentinel traps versus untreated controls. No evidence was found of autodissemination of pyriproxyfen from these applications to vegetation.[37]

Bifenthrin

Barrier treatments using a STIHL SR 420 backpack sprayer applied Talstar One (bifenthrin 7.9%) to vegetation in residential neighborhoods in Lexington, Kentucky, reduced *Ae albopictus* populations, but not *Cx pipiens* L. populations.[30] Mosquito populations were measured using a variety of sampling methods such as human landing collections, sweep nets, ovitraps, CDC gravid traps, and CDC light traps baited with CO_2. Bifenthrin was effective in controlling *Ae albopictus* for up to 6 weeks with an 85% reduction for bifenthrin versus untreated controls.[30]

In Santa Rosa Beach, Florida, Cilek[23] found that Talstar One (7.9% bifenthrin) applied with a modified pressure washer using Teejet nozzles, reduced mosquito populations (consisting of 18 species) in a treated area over 6 weeks, but statistically significant reductions varied from week to week. Following the application of bifenthrin, there was a 91% reduction in mosquito abundance in the treated area; however, during week 2 post treatment, more mosquitoes were collected in traps in the treated plot than in the untreated plot. Mosquitoes were collected using ABC light traps baited with CO_2.

In a study of vegetation barriers in the desert of Coachella Valley, California, vegetation treated with Talstar (bifenthrin 7.9%) resulted in significantly fewer mosquitoes collected in Encephalitis Virus Surveillance (EVS) traps baited with dry ice for 28 days following applications.[24]

Hurst et al[25] found that treating vegetation in the backyards of suburban homes in Queensland, Australia, with Bifex AquaMax (100 g bifenthrin/L) significantly reduced the numbers of *Ae vigilax* (Skuse) collected in light traps and human landing counts for 8 weeks following application. This supported another study[38] (cited in Hurst et al[25]) where Bistar 80SC (80 g bifenthrin/L) also significantly decreased *Ae vigilax* numbers in Hervey Bay, Queensland, for 6 weeks. However, numbers of other important human-biting species (ie, *Cx annulirostris* [Skuse], *Coquillettidia xanthogaster* [Edwards], and *Mansonia uniformis* [Theobold]) were not significantly reduced by the application.

The successful use of barrier treatments was reported at 4 sites over a 4-year period by AMCD in Florida using Talstar One (bifenthrin 7.9%).[26] Three field sites were treated using a hand compression sprayer and 1 site was treated with a flo-jet pump with a 40° flat fan nozzle. Mosquito populations including *Ae sollicitans, Ae taeniorhynchus, Ae albopictus, Ae atlanticus, Ae infirmatus, Cx nigripalpus* Theobald, *Psorophora columbiae* (Dyar and Knab), and *Culiseta melanura* (Coquillett) were measured at 2 sites using human landing counts and at 1 site using a CDC light trap baited with dry ice and at 1 site using a Mosquito Magnet X trap (MMX) with dry ice.[26] Regardless of the site or collection method, barrier applications significantly reduced mosquito numbers for up to 3 weeks.[26]

The efficacy of a private pest control company barrier applications of Bifen I/T (bifenthrin 7.9%) was evaluated using CO_2-baited CDC light traps and CO_2-baited BG Sentinel traps and larval surveillance at private residences in eastern North Carolina.[27] Overall, the number of mosquitoes was reduced significantly in treated versus untreated properties on average by 54% but as high as 74%. Differences were found between *Aedes* spp. (as high as 69%) and *Culex* spp. (32%) but *Anopheles* spp. and *Culiseta* spp. showed little or no difference between treated and untreated properties over the 16 week study.[27] In testing treated and untreated leaves, a greater

amount of residual bifenthrin was detected from treated properties; no correlation was observed between residual levels of bifenthrin and number of mosquitoes collected.

In St Augustine, Florida, a novel sprayer, 3WC-30-4P was tested[28] against floodwater mosquitoes with Talstar P (7.9% bifenthrin). Using CDC light traps to collect the mosquitoes in treated and untreated plots, mosquito numbers in treated and untreated areas were significantly reduced, for a 4-week period, with a mean reduction of 77%.[28] Also in St Augustine, vegetation was treated in a cemetery with Talstar P (bifenthrin 7.9%) and a STIHL SR 420 backpack sprayer.[29] Using BG Sentinel traps baited with BG lure and black oviposition cups, a significant reduction in the eggs and adults of *Ae albopictus* up to 4 weeks post application was reported compared with pre-application collections.[29]

Cypermethrin

In Italy, to find new ways to control *Ae albopictus*, 2 different machines were compared for barrier applications,[35] the Elite 14S-300 SprayTeam Machine and the Tartaruga 300/3 with 2 different insecticides, Microsin (cypermethrin 10%, tetramethrin 2%, PBO 15%) and Etox 20/20 CE (etofenprox 20%, tetramethrin 3%, PBO 15%). In the aforementioned study, the Tartaruga 300/3 outperformed the Elite 14S-300 with the former having a reduction of 60% in human landing counts after 14 days vurses 40% in the latter.

Conclusions

For more than 70 years, MCPs have taken advantage of the mosquito's resting behavior to target vegetation with residual applications of insecticides. Private pest control companies have had a long-standing role in mosquito control and routinely control mosquitoes in localized geographic areas such as private events (parties and weddings) and/or at private residences "on demand."[48] The barrier treatment industry, generally conducted by private pest control companies, has thrived, in part, due to off-patent inexpensive and effective pyrethroid adulticide AIs, such as bifenthrin. In addition, the IGR pyriproxyfen is gaining popularity in barrier treatments and, in some cases, synergists (eg, PBO) are being incorporated.

This review reflects the diversity of mosquito species targeted by MCPs, different methods used to test best practices, and the relatively limited number of effective insecticides currently available. Despite the volume of research on this topic, many details remain to be investigated and questions unanswered to improve the effectiveness of barrier treatments. A lack of understanding of where, when, and what species of mosquitoes rest in the barrier vegetation in varied habitats in different geographic locations is the most glaring gap in our knowledge. Most knowledge of barrier applications is based on indirect sampling of mosquitoes with traps or observation through landing collections, but a thorough understanding of mosquito resting, and types of vegetation they prefer, would allow for more targeted applications and limit potentially ineffective barrier applications. For example, more information is needed on the importance of treating tree canopies and if powered aspirators should be incorporated to collect mosquitoes instead of host-seeking traps. Some of the studies cited here lacked replication and we show the diversity of application methods used between studies; hence caution is advised when interpreting results. This highlights the need to develop standardized assessment methods for barrier treatments.

Three other important knowledge gaps include the extent to which barrier applications may (1) contribute to insecticide resistance, (2) affect risk of arbovirus transmission, and (3) affect non-target organisms. State and local health departments, MCPs, and private pest control companies should consider partnering with universities and the CDC to understand the extent to which barrier and other types of mosquito control treatments may be evaluated using standardized methods. Collaboration between different agencies potentially can improve targeted techniques for barrier applications, integrate novel control technologies to manage "backyard" mosquitoes, and potentially reduce the impact of mosquito-borne disease.

Due to the wide range of environmental and other factors that can potentially influence the effectiveness of an AI or formulated product used in barrier treatments, it is difficult to pinpoint which application method and AI/product would be most effective. It is known that rainfall decreases the length of time an AI is effective and plant species, plant density/type, and the equipment used to apply the insecticide all play a role in efficacy of mosquito suppression. In addition to increased collaboration, efforts should be made by organizations such as the American Mosquito Control Association (www.mosquito.org) to standardize laboratory bioassays, semi-field, and field study methods used to evaluate AIs/formulated products used in barrier treatments. Standardization of the methods will improve our ability to compare study results and allow for better interpretation of the efficacy of an AI in a given habitat. Methods to evaluate environmental impacts of the applications should also be standardized and used to regularly assess the impact on mosquito susceptibility to the AIs as well as the impact on non-target organisms (eg, bees). The effects of insecticide applications must be analyzed with respect to other environmental impacts on non-target organisms such as housing development and other sources of habitat loss. Both pest and vector mosquito species can be controlled using barrier treatments. Future studies should go beyond basic efficacy trials and attempt to target specific mosquito species of interest (ie, public health importance, nuisance) based on an understanding of their behavior (eg, resting areas, flight range). As for any MCP, insecticide resistance monitoring should take place routinely to ensure that the most efficacious AI/product is being used.

Author Contributions

All authors contributed to the literature search and wrote the manuscript.

REFERENCES

1. American Mosquito Control Association (AMCA). *Best Practices for Integrated Mosquito Management: A Focused Update*. Mount Laurel, NJ: AMCA; 2017.
2. World Health Organization (WHO). *Space Spray Application of Insecticides for Vector and Public Health Pest Control*. Geneva, Switzerland: WHO.
3. Qualls WA, Smith ML, Muller GC, Zhao TY, Xue RD. Field evaluation of a large-scale barrier application of bifenthrin on a golf course to control flood water mosquitoes. *J Am Mosq Control Assoc*. 2012;28:219–224.
4. Hoffman WC, Farooq M, Walker TW, et al. Canopy penetration and deposition of barrier sprays from electrostatic and conventional sprayer. *J Am Mosq Control Assoc*. 2009;25:323–331.
5. Perich MJ, Tidwell MA, Dobson SE, Sardelis MR, Zaglul A, Williams DC. Barrier spraying to control the malaria vector *Anopheles albimanus*: laboratory and field evaluation in the Dominican Republic. *Med Vet Entomol*. 1993;7:363–368.
6. Ginsburg JM. Outdoor protection from mosquitoes. *J NY Entomol Soc*. 1944;52:247–254.
7. Madden AH, Schroeder HO, Lindquist AW. Residual spray applications to salt-marsh and jungle vegetation for control of mosquitoes. *J Econ Entomol*. 1947;40:119–123.
8. Madden AH, Lindquist AW, Knipling EF. DDT residues on vegetation and ground litter for control of adult salt-marsh mosquitoes. *Mosq News*. 1945;5:100–104.
9. Madden AH, Lindquist AW, Travis BV, Knipling EF. Outdoor control of adult mosquitoes with DDT or pyrethrum applied with ground equipment. *Mosq News*. 1946;6:7–11.
10. Ludvik GF. Barrier strip and pre-flood treatments with DDT to control *Anopheles quadrimaculatus*. *J Econ Entomol*. 1950;43:516–519.
11. Hoffman RA, Lindquist AW. Residual and space sprays for the control of snow-water *Aedes* mosquitoes in camp areas. *Mosq News*. 1952;12:87–91.
12. Quarterman KD, Jensen JA, Mathis W, Smith WW. Barrier-strip spraying for the control of rice field mosquitoes. *J Econ Entomol*. 1955;48:107–108.
13. Bidlingmayer WL, Schoof HF. Outdoor residual treatments of premises for control of salt-marsh mosquitoes. *Mosq News*. 1956;16:17–19.
14. Helson BV, Surgeoner GA. Permethrin as a residual spray for adult mosquito control. *Mosq News*. 1983;43:164–169.
15. Anderson AL, Apperson CS, Knake R. Effectiveness of mist-blower applications of malathion and permethrin to foliage as barrier sprays for salt marsh mosquitoes. *J Am Mosq Control Assoc*. 1991;7:116–117.
16. Cilek JE, Hallmon CF. Residual effectiveness of pyrethroid treated foliage against adult *Aedes albopictus* and *Culex quinquefasciatus* in screened filed cages. *J Am Mosq Control Assoc*. 2006;22:725–731.
17. Amoo AOJ, Xue RD, Qualls WA, Quinn BP, Bernier UR. Residual efficacy of field-applied permethrin, d-phenothrin, and resmethrin on plant foliage against adult mosquitoes. *J Am Mosq Control Assoc*. 2008;24:543–549.
18. Richards SL, Volkan JK, Balanay JAG, Vandock K. Evaluation of bifenthrin and deltamethrin barrier sprays for mosquito control in eastern North Carolina. *J Med Entomol*. 2017;54:1659–1665.
19. McMillan BE, Bova JE, Brewster CC, Gallagher NT, Paulson SL. Effects of plant species, insecticide, and exposure time on the efficacy of barrier treatments against *Aedes albopictus*. *J Am Mosq Contr Assoc*. 2018;34:281–290.
20. Bengoa M, Eritja R, Lucientes J. Laboratory tests of the residual effect of deltamethrin on vegetation against *Aedes albopictus*. *J Am Mosq Control Assoc*. 2013;29:284–288.
21. Qualls WA, Xue RD. Laboratory evaluation of seven commercial barrier treatment products against *Aedes albopictus*. In: *Technical Bulletin of the Florida Mosquito Control Association*. Deleon Springs, FL: E.O. Painter Printing Company; 2013: 29–32.
22. Trout RT, Brown GC. Impact of residual insecticide applied to upper story vegetation on resting adult mosquitoes (Diptera: Culicidae). *Florida Entomol*. 2009;92:91–98.
23. Cilek JE. Application of insecticides to vegetation as barriers against host-seeking mosquitoes. *J Am Mosq Control Assoc*. 2008;24:172–176.
24. Britch SC, Linthicum KJ, Wynn WW, et al. Evaluation of barrier treatments on native vegetation in a southern California desert habitat. *J Am Mosq Control Assoc*. 2009;25:184–193.
25. Hurst TP, Ryan PA, Kay BH. Biflex AquaMax applied as barrier treatments for managing mosquito populations in suburban residential properties in southeast Queensland. *J Med Entomol*. 2012;49:1021–1026.
26. Qualls WA, Smith ML, Xue RD. Successful applications of barrier treatments using bifenthrin against mosquitoes in St. Johns County, Florida from 2006 to 2009. In: *Technical Bulletin of the Florida Mosquito Control Association*. DeLeon Springs, FL: E.O. Painter Printing Company; 2013: 33–37.
27. VanDusen AE, Richards SL, Balanay JAG. Evaluation of bifenthrin barrier spray on foliage in a suburban eastern North Carolina neighborhood. *Pest Manag Sci*. 2015;72: 1004–1012.
28. Fulcher AM, Farooq M, Smith ML. Evaluation of a new spraying machine for barrier treatment and penetration of bifenthrin on vegetation against mosquitoes. *J Am Mosq Control Assoc*.2015;31: 85–92.
29. Bibbs C, Anderson C, Smith ML, Xue RD. Bifenthrin barrier spray against *Aedes albopictus* around and urban cemetery, St. Augustine, Florida. In: *Technical Bulletin of the Florida Mosquito Control Association*. DeLeon Springs, FL: E.O. Painter Printing Company; 2016: 76–80.
30. Trout RT, Brown GC, Potter MF, Hubbard JL. Efficacy of two pyrethroid insecticides applied as barrier treatments for managing mosquito (Diptera: Culicidae) populations in suburban residential properties. *J Med Entomol*. 2007;44: 470–477.
31. Doyle MA, Kline DL, Allan SA, Kaufman PE. Efficacy of residual bifenthrin applied to landscape vegetation against *Aedes albopictus*. *J Am Mosq Control Assoc*. 2009;25:179–183.
32. Allan SA, Kline DL, Walker T. Environmental factors affecting efficacy of bifenthrin-treated vegetation for mosquito control. *J Am Mosq Control Assoc*. 2009;25:338–346.
33. Li CX, Wang ZM, Dong YDT, et al. Evaluation of lambda-cyhalothrin barrier spray on vegetation for control of *Aedes albopictus* in China. *J Am Mosq Control Assoc*. 2010;26:346–348.
34. Muzari OM, Adamczyk R, Davis J, Ritchie S, Devine G. Residual effectiveness of λ-cyhalothrin harbourage sprays against foliage-resting mosquitoes in North Queensland. *J Med Entomol*. 2014;51:444–449.
35. Marini L, Baseggio A, Drago A, et al. Efficacy of two common methods of application of residual insecticide for controlling the Asian Tiger Mosquito, *Aedes albopictus* (Skuse), in urban areas. *PLoS ONE*. 2015;10:e0134831.
36. Unlu I, Williams GM, Rochlin N, et al. Evaluation of lambda-cyhalothrin and pyriproxyfen barrier treatments for *Aedes albopictus* (Diptera: Culicidae) management in urbanized areas of New Jersey. *J Med Entomol*. 2018;55: 472–476.
37. Suman DS, Farajollahi A, Healy S, et al. Point-source and area-wide field studies of pyriproxyfen autodissemination against urban container-inhabiting mosquitoes. *Acta Trop*. 2014;135:96–103.
38. Standfast H, Fanning I, Maloney L, Purdie D, Brown M. Field evaluation of Bistar 80SC as an effective insecticide treatment for biting midges (Culicoides) and mosquitoes infesting peri-domestic situations in an urban environment. *Bull Mosq Cont Aus*. 2003;15:19–33.
39. Gibson J, Xue RD, Smith ML. Field comparison of thermal fog application of sumithrin and barrier spraying of Talstar against *Aedes albopictus* in residential yards, St. Augustine, Florida. In: *Technical Bulletin of the Florida Mosquito Control Association*. DeLeon Springs, FL: E.O. Painter Printing Company; 2016: 96–98.
40. Knipling EF. DDT insecticides developed for use by the armed forces. *J Econ Entomol*. 1945;33:205–207.
41. Ginsburg JM. A survey of insecticides used in country-wide mosquito control in 1955. *Mosq News*. 1956;16:137–138.
42. Quarterman KD. The use of insecticides against adult mosquitoes. *Mosq News*. 1957;17:254–257.
43. Geib AF. Importance of organic phosphorus insecticides in mosquito control in California. *Mosq News*. 1957;17:166–167.
44. Sanders HJ, Taff AW. Staff industry collaborative report allethrin. *Ind Eng Chem*. 1954;46:414–426.
45. Elliott M. Properties and applications of pyrethroids. *Environ Health Perspect*. 1976;14:1–13.
46. Cooperband MF, Allan SA. Effects of different pyrethroids on landing behavior of female *Aedes aegypti, Anopheles quadrimaculatus*, and *Culex quinquefasciatus* mosquitoes (Diptera: Culicidae). *J Med Entomol*. 2009;46:292–306.
47. Farooq M, Walker TM, Heintschel BP, et al. Impact of electrostatic and conventional sprayers characteristics on dispersion of barrier spray. *J Am Mosq Control Assoc*. 2010;26:422–429.
48. Buettner WO. The pest control operator's place in mosquito control. *Mosq News*. 1953;13:72–74.