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REVIEW ARTICLE

Ultra-low-volume space sprays in mosquito control: a critical review

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Abstract. The availability of tools to control mosquito (Diptera:Culicidae) vectors that transmit disease is often limited by a variety of economic, environmental and social issues. In emergency conditions (epidemics, hurricanes, floods etc.), the application of pesticides as space sprays (either by ground or air) is the common method of choice in order to rapidly limit adult local mosquito production in the affected area. Space spray application now employs ultra-low-volume technology for the control of adult mosquitoes. However, the use of space sprays often raises social and environmental concerns by the general public that is served.

This review will define and illustrate modern ultra-low-volume technology for the purpose of application as a space spray, as well as describing the engineering controls that have been developed to minimize the environmental impact. The primary social concern is validity and efficacy of application. To address this point, the review will attempt to synthesize the global literature to address the effectiveness of space sprays to significantly impact mosquito vectors in relation to human disease.

Key words. Adulticide, dengue fever, malaria, non target, ultra low volume, West Nile Virus.

Introduction

Ultra-low-volume (ULV) sprays are pesticide applications against the flying adult vector. These sprays do not target the eggs larva or pupae, only the insect on the wing, meaning that sequential applications are necessary to control adults emerging from immature stages. The first issue to be addressed is the correct definition of ULV. An ULV application is the minimum effective volume of the formulated product without any further dilution. If the insecticide is diluted by the operator the application is considered low volume (LV) or high volume (HV) (Mount, 1998). The insecticide concentration varies depending on the amount of active ingredient in the formulation, ranging from 2% with some of the pyrethroids to 95% with the organophosphates. The volume applied (i.e the application rate) is dependent on the concentration and toxicity of the compound to the target species (Mount, 1998). Indoor residual treatments (IRS) and barrier treatments to vegetation are classified as LV or HV applications depending on the level of dilution and will not be discussed in this review. Moreover, thermal fogging, which is commonly confused with ULV sprays, requires significant dilution of the formulated product, making them LV or HV applications depending on the dilution rate; again thermal applications will not be discussed in this review.

Scientists began to look at the application of LV insecticides in Africa against Tsetse flies using DDT (Yeo & Thompson, 1954). The first ULV sprays were aerial, conducted for agricultural purposes; using technical malathion for the control of various forage crop insects, such as grasshoppers and the cereal leaf beetle (Messenger, 1963). Knapp & Roberts (1965) conducted one of the foremost forays into aerial ULV applications against salt-marsh mosquitoes; with 95% technical malathion successfully applied at 219 mL/ha. In the same exploratory era, Glancey *et al.* (1965) conducted tests to evaluate other insecticides and mixtures as ULV aerial sprays expanding the armory and providing an array of chemistries for aerial applications. Studies over the following years confirmed that high volumes of carrier were not necessary to disperse the active ingredient. Mount & Lofgren (1967a) compared the effects of ULV naled applied at 117–467 mL/ha to HV

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7 L/ha in a water carrier against adult salt marsh *Aedes taeniorhynchus* mosquitoes. Their results showed that ULV and diluted sprays of naled were equal in effectiveness (0.156 and 0.132 kg ai/ha, respectively, for 90% control). Another comparison of ULV using propoxur (Baygon, Bayer, Kansas city, MO, U.S.A.) at 234 mL/ha to HV 4.7 L/ha in a water carrier at equal doses of 0.06 kg/ha against *Aedes sollicitans* (Walker) produced 92% and 88% reductions, respectively (Knapp & Rogers, 1968).

The success of aerial ULV prompted the development of appropriate technologies for ground applications. One of the first machines was a modified, non-thermal aerosol generator [Curtis(R) 55 000; Curtis Dyna-Fog Ltd., Westfield, IN, U.S.A.] developed by the U.S. Army Engineers Research and Development Laboratories, Fort Belvoir, VA, U.S.A. (Edmunds *et al.*, 1958). With this apparatus ULV applications of malathion and naled (14–36.5 mL/ha) were shown to be equal to or better than the same dose in LV applications (1–0.8 L/ha) against adult salt-marsh mosquitoes (Mount *et al.*, 1968). These results were confirmed by Mount & Lofgren (1967b), Mount *et al.* (1968, 1969, 1970), Taylor & Schoof (1968), McNeill & Ludwig (1970), Mount & Pierce (1971), Taylor & Schoof (1971), Rathburn & Boike (1972) and Husted *et al.* (1975) demonstrating that diluents were not critical to mosquito control.

The ULV ground aerosol method was rapidly advanced by the development of commercial ULV generators and the registration of technical or undiluted formulations of insecticide for ULV ground aerosol application by the United States Environmental Protection Agency (US-EPA). The ULV ground aerosol method was rapidly adopted by mosquito control organizations throughout the world. Both ground and aerial ULV applications have been the standard method of mosquito adulticiding worldwide for more than 45 years.

There are a large number of different devices available today to generate a ULV space spray. The most important improvements have focused on the pumps metering devices and the specialized nozzles required to atomize undiluted insecticides into droplets small enough to create an aerosol that will drift through the target zone. The incorporation of Global Information Systems (GIS) and Global Positions systems (GPS) have improved surveillance techniques for targeting the applications and automated dosing systems controlled by GPS sensors for greater precision and accountability (Lowe, 2006; Nawrocki, 2004). One of the most significant developments for aerial applications is the near-wake model developed for the pesticide dispersion model AGDISP. The wake model is a Lagrangian model that tracks the movement of spray material from nozzles at the aircraft until they either deposit or drift downwind. The model includes the innovative step of developing ensemble-averaged turbulence equations to predict the growth of the spray cloud during the calculations, and thus eliminates the need for a random component in the solution procedure. In its current configuration, AGDISP includes simplified models for the effects of the aircraft wake and aircraft-generated and ambient turbulence, and a transition to a Gaussian model for the prediction of deposition to 20 km downwind (Teske & Thistle, 2004).

Neither the different types of machinery nor the technological developments shall be discussed in this review. Instead this review will define the parameters that govern the effective dispersal of the insecticide, the non-target impact of that spray and the influence of ULV sprays on disease transmission.

Droplet size

Droplet size is a principal factor affecting the efficiency of space sprays for the control of adult mosquitoes as droplet size is directly related to the transport and collection efficiency (Mount, 1970). Two of the most important requirements for an optimum droplet size are that droplets must be small enough to be produced in sufficient numbers for probability of contact and large enough to impact or impinge readily on the body surface of adult mosquitoes (Mount, 1970).

Several studies have found that for ULV to be efficacious the optimal droplet size should be less than 20 μm in diameter. Using scanning electron microscopy, Lofgren *et al.* (1973) found that droplets ranging from 2 to 16 μm in diameter impinged on the wings and antennae of mosquitoes flying through ULV aerosol clouds, and although droplets up to 32 μm in diameter were found on slides, they were not found on mosquitoes. Unpublished observations by the author agreed that smaller drops were visible on the hairs and wing tips. However, a fluorescent tracer was used and the insect legs of exposed *Ae. taeniorhynchus* fluoresced indicating that the pesticide deposited on the lipophilic cuticle was rapidly adsorbed. The physics of particulate collection supports this theory. The collection efficiency of a droplet is defined by a complex interaction between the size of the droplet and the obstacle in its path and their relative velocity (May & Clifford, 1967). In general, collection efficiency increases with droplets size and the velocity of the droplet relative to that obstacle and decreases as the obstacle increases in size (Matthews, 1992). Large drops have increased impaction efficiency, but for a given volume of liquid there will be fewer drops reducing probability of contact, and also reducing duty time as a result of an increased sedimentation velocity.

For a given volume where there is 1 100-μm droplet there will be 8 50-μm 64 25-μm and 512 12.5-μm droplets. The size of the droplet not only defines the number produced for a given volume but also the duty time of that droplet. A droplet of 10 μm with a specific gravity of one will have a 17 min fall time from 3 m (Matthews, 1992). The application of ULV sprays from a ground platform depends entirely on longitudinal winds for dispersal of the insecticide. Table 1 shows the theoretical drift (based on Stokes' law) of droplets of technical malathion during a 1.2-m fall in stable atmospheric conditions at wind velocities ranging from 1.6 at 4 k.p.h. A droplet size of about 10 μm or less is necessary to achieve swaths of at least 150 m during low wind velocities (3.2 k.p.h. or less).

Accordingly, the optimum-sized droplet for mosquito control with field-applied ground ULV has been determined to be in the range of and 5–25 μm (Mount *et al.*, 1996). This size distribution may be optimum for truck-based sprays, but not for aerial. Ground-based ULV sprays are placed directly into

Table 1. Distance travelled by three different-sized malathion droplets, at three different wind speeds from a 1.3 m height.

Droplet diameter (μm)	Distance meters droplet would travel considering the wind speed (k.p.h.)		
	6.4	3.2	1.6
2.5	9817	4908	2454
10	575	288	144
25	100	50	25

the environment where mosquitoes are active. The equivalent process for aerially applied sprays is more complex as effective applications rely on a combination of aircraft turbulence (descent of vortices), atmospheric mixing and droplet sedimentation to bring the spray down from spray altitude into the target zone. Using operational evaluations, several programs have settled on a range of between 25 and 35 μm as being the optimal volume median diameter (VMD) for aerial adulticiding sprays (Barber *et al.*, 2008). One of the first studies that looked at canopy penetration of aerial sprays was conducted by Himel & Moore (1967). Using a fluorescent particle tracer method they learned that 93% of spruce budworms, *Chonstoneura fumifcrana* (Clemens), collected had not been contacted by any droplets larger than 50 μm in diameter even although they used a broad-spectrum spray whose droplets ranged from about 1–3 μm to 300–400 μm.

With the implementation of new adulticide label requirements in 2006 the spray plume statistics have been changed. The diameter volume (Dv) has now replaced the volume median diameter (VMD). The diameter volume is a decimal value between 0 and 1 which relates the volume proportion of the spray cloud to the drop diameter. The diameter volume for the size drop at which 50% of the spray volume is composed of drops equal to in diameter and smaller, written as $\mathrm{Dv}_{(0.5)}$, represents the same value as VMD. The diameter volume can provide the size drop at which 10% of the spray volume is composed of this drop diameter and smaller [$\mathrm{Dv}_{(0.1)}$] as well as the 90% value [$\mathrm{Dv}_{(0.9)}$]. The combination of $\mathrm{Dv}_{(0.1)}$, $\mathrm{Dv}_{(0.5)}$ and $\mathrm{Dv}_{(0.9)}$ provides an understanding of the droplet size distribution. The droplet sizes that are effective for ground adulticiding have $\mathrm{DV}_{0.5}$'s of 12–20 μm. The most effective drop sizes for aerial adulticiding are $\mathrm{DV}_{0.5}$'s of 25–40 μm depending on operational parameters, target species and target habitat and specific gravity of the insecticide (Bonds, 2008).

Meteorology

Both ground and aerial adulticiding produce a spray cloud of ultra-fine drops that have a low sedimentation velocity leaving them highly susceptible to atmospheric events. Where aerial adulticiding differs from ground applications is that the spray is atomized above the target zone rather than within making aerial adulticiding considerably more complicated.

During aerial applications the influence of the spray platform must also be considered. The atomized spray drops are entrained within the wingtip or rotor wash vortices of the aircraft. This energetic turbulence produced by the aircraft sinks towards the ground, taking the spray cloud with it, before dissipating. The descent distances and life of the vortices before decay vary between aircraft and atmospheric conditions but typically drop 30–50 feet from the aircraft and last several minutes. In some aircraft under very stable atmospheric conditions, the vortices' decay more slowly and vortex descent distances can exceed 100 feet lasting more than 5 min (Latham & Barber, 2007).

Once released from the dissipated vortices, the spray cloud is now subject to general atmospheric turbulence which dilutes the spray vertically and horizontally. Droplet dispersal or mixing is then accomplished by atmospheric turbulence. Gravity will move droplets down and the mean wind will govern longitudinal distance, but the concentration of droplets in a given volume of air will be determined by turbulent mixing (Thistle, 2000).

The ULV application must occur at times relevant to the target mosquito activity. The atmospheric stability changes throughout the day from unstable to neutral to stable at dusk and vice versa at dawn. It is critical that stability be understood. It can be described by the movements of a parcel of air relative to the air that surrounds it. In an unstable atmosphere temperature decreases with height. A rising parcel of air, therefore, will be less dense than its surroundings and rise. Consequently, unstable atmospheres are associated with strongly convective motions. Unstable conditions would cause the mosquitocidal cloud to dilute and ascend out of the target area. In stable conditions the opposite is true, the temperature tends to increase with altitude so, if a parcel of air goes up it will be denser and sink, and when less dense than the surrounding air it will rise hence the parcel of air stays relative to air with the same density. A consequence of this is that turbulence is suppressed, and the cloud will concentrate in the release zone. In neutral conditions there is no temperature gradient and this can be considered the transitory stage. Parcels of air have the same density as their surroundings and experience no buoyancy forces, irrespective of vertical position and motion (Bache & Johnstone, 1992). Neutral to weakly stable conditions are considered ideal for ULV spraying as long as there is a longitudinal motion to move the spray through the target area. This changing atmosphere has a significant impact on the dispersal of adulticide applications. Meteorology, therefore, should be considered one of the primary parameters controlling efficacy of an ULV application.

Spray droplets are also subject to the forces of gravity with a sedimentation velocity related to their size and density. Under stable night-time conditions with little vertical movement in the atmosphere the sedimentation velocity may play a significant role in the droplets movement towards the target zone (near the ground) and significantly affect the peak deposition numbers.

Failures in mosquito adulticiding often occur because of an over simplification of the system within which we work. Where the target area is open and with few obstacles obstructing air flow specifically from ground applications, control is usually achieved. However, mosquitoes prefer to reside in a harborage, often in a plant canopy or a residence. The target, therefore, is the porous vegetative media between the air aloft and the ground. The obstacles can filter out the spray and shelter the mosquitoes from direct impact with the spray. The inclusion of canopy is most pertinent considering that *Culex nigripalpus*, the primary vector of West Nile Virus (WNV) within FL, U.S.A., is rarely found outside a vegetative refuge (Bidlingmayer *et al.*, 1974; Day *et al.*, 1994). Similarly the primary vector in dengue fever is rarely found outside of the urban sprawl.

The dynamics of vegetative canopies are better understood than urban areas but the fundamental theories could be relevant to both habitats. The energy in the boundary layer which carries the spray does not necessarily transfer equally into the canopy (Curtis & Mason, 1988; Barber *et al.*, 2007). Investigations into the dispersal of adulticides more frequently occur in the open owing to the simplicity of this model.

Clearly the meteorology at the time of application must be considered; and the application should wait for conditions conducive to successful dispersal of the spray. Every effort should be made by operators and researchers alike to equip and educate themselves in the effects of meteorology on adulticiding. The calculation and estimation of long range movement can be provided by models but it also needs to be validated by dedicated research projects (Dukes *et al.*, 2004a, 2004b). Sophisticated advances in technology are driving a change in ULV applications. The ultimate goal is targeted applications with minimized non-target exposure to insecticide (Slatter, 2002).

Timing

As the technique targets the mosquito on the wing, the timing of ULV applications needs to be precise, because different species are active at different times. Many mosquito species fly in the crepuscular hours to avoid desiccation. Measurements of *Aedes melanimon, Culex tarsalis* and *Culex quinquefasciatus* at rural locations during the late spring (May to June) and early fall (September to October) showed that host-seeking activity was most prominent from 1 to 2 h after sunset. However, during mid-summer (July to August) when evening air temperatures were warmer, peak host-seeking activity was delayed by 1–4 h (Meyer *et al.*, 1986). Studies on host seeking in *Culex salinarius* indicated that the species was most active within 2 h after sunset, with a significant reduction in host-seeking activity during the remainder of the night, and no increase in activity was noted prior to dawn. (Slaff & Crans, 1981). *Culex nigripalpus* crepuscular-nocturnal species was most active for the 3 h after sunset and again just before sunrise (Day & Curtis, 1994).

Common domestic mosquitoes, *Aedes aegypti* and *Aedes albopictus*, are day biters or ‘diurnal’. They tend to have peaks in activity during the hours after sunrise and hours before sunset, with lesser activity during the heat of the day and little to no activity at night. Diet-landing periodicity of domestic *Ae. aegypti* (L.) in Trinidad, West Indies, was monitored using human bait during January to August 1980. The periodicity of females was predominantly diurnal (95.2% arriving during daylight twilight) and bimodal, with consistent peaks at 06.00–07.00 and 17.00–18.00 hours. The time of insecticidal ULV adulticiding should coincide with peaks in landing periodicity of the *Ae. aegypti* adults. (Chadee, 1988). In studies by Fox (1980) in Puerto Rico and by Hudson (1986) in Surinam, failure to suppress *Ae. aegypti* populations may have been as a result of a lack of synchrony between ULV spraying and mosquito flight activity as spraying was conducted at 18.00–22.00 hours for convenience (Hudson, 1986) when the mosquitoes were probably resting. The *Anopheline* malaria vectors typically exhibit a ‘nocturnal’ activity pattern. They are most active in the middle of the night when their hosts are sleeping, and usually exhibit no daytime activity. Timing is not just related to time of the day. Other behavioural traits should be considered so that the application can coincide with flight activity. For example, the principal vector of WNV and SLE in Florida, *Cx. Nigripalpus*, is very sensitive to meteorological change. Studies have shown that increased humidity and temperature increases activity (to a limit, above which activity decreases); increased wind decreases activity; and lunar illumination increases activity (Day & Curtis, 1994).

ULV efficacy

With ULV applications there is the unrelenting question as to whether it works. Considering the issues already discussed in terms of the physical and biological parameters required to effectively move the spray through a target zone, the first question to ask is what habitats are the most problematic. Obstructions are going to have a significant impact on control and the average mortality of caged *Ae. aegypti* for example has been shown to be 95.5% and 49% in open and sequestered locations, respectively (Andis *et al.*, 1987). The resting behaviour of *Ae. aegypti* (L.) makes it a difficult insect to control. Perich *et al.* (2000) investigated in 14 districts of Panama City, Panama, in relation to ground ULV applications of malathion. Adults primarily rested inside the premises (75.1%) at a distance >6 m from the street (86.4%). Both sexes rested mainly in bedrooms, living rooms and bathrooms. Although the small ULV aerosol droplets penetrated all indoor resting sites of *Ae. aegypti*, the quantities were not sufficient for control. Research by the same author compared ground truck and aerial applications of 91% malathion ULV against *Ae. aegypti* in the Dominican Republic. Evaluations were by ovitraps and indoor collections and caged mosquitoes. Giglioli (1979) stated an immediate, minimum 97% reduction of adult *Ae. aegypti* is necessary to control a dengue epidemic. Considering this statistic Perich *et al.* (1990) found that, neither ground nor aerial applications effected such a reduction.

Vegetation can also provide a harborage and reduce mortality. Reddy *et al.* (2006) investigated the effects of ground applications for the suppression of reproductive activity of *Cx pipiens pipiens* and *Culex restuans* mosquitoes in suburban sites The target populations were fully susceptible to the insecticide and the road network generally gave adequate opportunity for insecticidal coverage. However, poor results showed that the aerosol plume failed to contact the target mosquitoes concluding that such insecticidal aerosols, delivered from the road, may not effectively enter the target site and, therefore, not be able to reduce transmission of WNV (Reddy *et al.*, 2006). Control failure in vegetated habitats may be caused by the following two factors. First, as suggested by Taylor & Schoof (1971), vegetation is a likely filter of the spray, leading to a reduction in the amount of pesticide available for impaction upon a mosquito. Curtis & Mason (1988) noted that reduced wind speed in the canopy would reduce impaction efficiency and may have been a contributing factor for reduced mortality in a vegetated environment. According to Mount (1998), malathion applied at similar rates provided greater than 90% mean control at both the low and high rates in the open field, but both rates dropped to between 34% and 67% in the vegetation. Barber *et al.* (2007) saw that Permanone 30 : 30 gave a 60% mean control in the open at the low rate, but 95% at the higher rate. In the vegetation, both rates produced no better than 29–34% mortality. These results for malathion compare with previous studies in both open field and vegetation. Permanone 30 : 30 at the higher rate also compared well with results tabulated by Mount (1998).

Many studies that experimentally look at the effect of non-sequential applications do not show ULV applications to be effective for the suppression of wild mosquito populations. Operational studies with repeated ULV inputs, however, show a more positive outcome. A study was initiated in New Orleans to evaluate the effectiveness of a single aerial ULV spraying (cythion) for the control of *Ae. aegypti* and *Cx quinquefasciatus.* This resulted in an initial 61% decrease in the number of ovitraps positive for *Ae. aegypti* eggs and a reduction of 73.6% for *Cx quinquefasciatus* after two consecutive malathion treatments. The ovipositional activity of *Ae aegypti* and *Cx quinquefasciatus* were suppressed for 7 days for *Ae. aegypti* and 5 days post-spray for *Cx quinquefasciatus.* The conclusion was that control was transient and, in the event of an epidemic, multiple treatments may be required to decrease vector abundance below the threshold (Andis *et al.*, 1987).

Where applications are repeated control should be achieved. Lofgren *et al.* (1970) applied 95% malathion twice 4 days apart as a wide area aerial application. *Aedes aegypti* densities were high with pretreatment landing counts of 8.6 adults/man h and premise indices between 58% and 94%. The landing rate of *Ae. aegypti* was greatly reduced after each application (95% and 99%, respectively); reductions remained at 88–99% for the 10 day post-application observation period. All ovitraps within the treated area were negative for 4 days after the first application. Only 8% of the female mosquitoes dissected post-treatment were parous compared with 30% pre-treatment and 40% in the check area. These high levels of control of *Ae. aegypti* populations indicated that the method could be used for vector control during outbreaks of dengue hemorrhagic fever (DHF).

Multiple applications are particularly necessary for *Ae. aegypti* and the dengue because the virus can be transmitted trans-ovarially. Vectors, therefore, must be exposed to successive treatments performed at intervals shorter than the extrinsic incubation period (Reiter & Nathan, 2001). Taking into consideration the interval between emergence and the first bloodmeal as well as the incubation period of dengue virus in the mosquito, it is probably unnecessary to re-treat an area less than 8–10 days after the initial treatment; thus treatments can be spaced more efficiently and operational costs can be reduced.

Lothrop *et al.* (2008) found that factors contributing to the success of their aerial treatments included the ability of the aircraft to reach large acreage not accessed by road, and treatment of a large acreage. Moreover, in this previous study, the application was repeated 26 times, over a period of 40 nights.

Using ULV applications for emergency vector control during disease outbreaks does not exclude the necessity for inter-epidemic environmental control with active participation of the community (Gratz, 1991). It has been shown that if properly carried out, ULV concentrates can achieve an immediate and persistent control, particularly if sequential applications are made. Wherever possible integrated control that makes use of all appropriate and feasible methods should be carried out against *Ae. aegypti* populations. Inhabitants of dengue endemic areas should be encouraged to dispose of undesired containers wherever possible. Where this does not achieve the aim of reducing *Ae. aegypti* adult populations, well-directed, efficient adulticiding should be carried out (Gratz, 1999).

The non-target impact of ULV space sprays

In terms of human health effects most studies are modelled as opposed to any direct measurement of effect. The subsequent risk assessments are then used to define applications rates and limits later ruled by the insecticide label. Schleier *et al.* (2009) used two-dimensional probabilistic risk assessment methodologies to evaluate three pyrethroid insecticides pyrethrins, two organophosphate insecticides and piperonyl butoxide (PBO) applied by a truck-mounted ULV sprayer. Results support the findings of previous studies that the risks to humans from adult mosquito management are most probably negligible, and that the human-health deterministic risk assessment is most likely sufficiently conservative. Peterson *et al.* (2006) evaluated documented health effects from WNV infection and ULV applications and determined potential population risks based on reported frequencies. Potential acute (1-day) subchronic (90-day) multiroute residential exposures from each insecticide were determined for several human subgroups during a WNV disease outbreak scenario. We then compared potential insecticide exposures to toxicological and regulatory effect levels. Risk quotients (RQs, the ratio of exposure to toxicologic effect) were <1.0 for all subgroups. Acute RQs ranged from 0.0004 to 0.4726, and subchronic RQs ranged from 0.00014 to 0.2074. Results from this risk assessment and the current weight of scientific evidence indicate that human-health risks from residential exposure to mosquito insecticides are low and are not likely to exceed levels of concern. Furthermore, their results indicate that, based on human health criteria, the risks from WNV exceed the risks from exposure to mosquito insecticides.

Other flying insects do not appear to be affected by mosquitocidal sprays if the body mass is larger than that of a mosquito (Boyce *et al.*, 2007). Field trials during a recent aerial application in California found there to be no effect of spraying on non-target sentinel species including dragonflies (*Sympetrum corruptum*), spiders (*Argiope aurantia*), butterflies (*Colias eurytheme*) and honeybees (*Apis mellifera*). By contrast, significantly higher diversity and numbers of non-target arthropods were found on ground tarps placed in sprayed vs. unsprayed areas. All of the dead non-target species were small-bodied arthropods (Boyce, 2007). A similar study using just ground tarps during an aerial application showed that larger number and a greater diversity of arthropods were recovered from tarps in the ULV spray area. The observed mortality was approximately 10-fold greater than in the control area. Mortality of sentinel mosquitoes in the treatment and control areas averaged 96% and <1%, respectively, at 24 h post-exposure.

Ground contamination on the other hand is another matter. Primarily the concern lies with the pyrethroids which do pose a risk to some aquatic species, especially invertebrates. Resmethrin for example is highly toxic to lobsters (*Homarus americanus* H. Milne Edwards) and long-term exposure to levels as low as 0.1 μg L^{-1} result in compromised behaviour (Zulkosky *et al.*, 2005), immune function and increased stress-related hormone levels (De Guise *et al.*, 2005). Resmethrin was detected in Long Island Sound after terrestrial spraying events (Zulkosky *et al.*, 2005) but rarely found at toxic levels (actual levels ranged from 1.7 to 980 ng L^{-1}). Tietze *et al.* (1991) found that mosquitofish (*Gambusia affinis* Baird and Girard) suffered mortality at field application rates. However, several researchers have argued that neither acute nor chronic toxicity were likely to occur under field conditions because of the short half-life of resmethrin in water (Rand, 2002) and the reduced concentrations of aerial applications when they reach the water surface (Tietze *et al.*, 1991).

Under laboratory conditions, in water without particulate matter, pyrethroid insecticides have a high toxicity to fish and aquatic invertebrates. The pyrethroids have very low water solubility/high lipophilicity, and are, therefore, rapidly and strongly adsorbed to particulate material. In the adsorbed state their bioavailability to aquatic organisms is greatly reduced. Consequently, under field conditions the aquatic impact of these insecticides is likely to be much less than might be predicted by laboratory acute chronic toxicity test data. Over the past 10 years a large number of aquatic field studies have been carried out with pyrethroids, in natural farm ponds, streams and lakes and mesocosms, also in experimental ponds and enclosures. After agricultural applications of the pyrethroid insecticides, spray drift run-off may produce minor effects upon aquatic organisms. Algae, microorganisms, annelids, gastropods and fish are unaffected, but impact upon certain zoo-plankton and aquatic stages of insects. However, with products for which realistic field studies have been reported, the effects are mostly transient and unlikely to cause adverse changes in the productivity of aquatic ecosystems (Hill, 1989). However, there is evidence that the toxic effects of permethrin associated with sediment could have caused failure of benthic species to re-colonize some areas for up to 6 weeks after application. In the field trial studied by Kingsbury & Kreutzweiser (1979) surveys of sediment found permethrin levels of up to 10 μg/kg in sediment 28 days after treatment. Similarly, Rawn (1981) found concentrations of permethrin in sediment of 4.9 μg/kg dry weight 323 days after artificial pools had been treated with permethrin at 28 g/ha. Neither study determined whether permethrin was in a form which would be toxic to biota.

Field trials using wetland mesocosms were either exposed to repeated aerial pyrethrin sprays or were protected by lids. Invertebrates in screened cages were placed in mesocosms and directly into wetlands. Caged adult mosquitoes were used to verify that sprays drifted over mesocosms. There were no detectable effects of synergized pyrethrin on 36-h survival of Daphnia or mayflies, but most exposed adult mosquitoes died. Some exposed sediments yielded pyrethrin (<34.5 ng g/L); most showed piperonyl butoxide (PBO) (<14.9 ng g/L). Deposition of aerosolized 25% pyrethrin +5% PBO may contaminate wetlands, but its application at rates used for mosquito control did not produce detectable effects on indicator species (Lawler *et al*., 2008). Similarly Jensen et al. (1999) found non-detectable concentrations of pyrethrins and permethrin in water samples from wetlands before and after truck-mounted ULV applications.

Disease impact

So what does all of this information give us regards to the ultimate goal, the reduction of disease in the human population? There are a large number of trials that have studied the effectiveness of ULV sprays in terms of knockdown of the mosquito population. The direct effect on disease transmission is not so well documented. It would be reasonable to assume that if there is a reduction in mosquito numbers, however, there has to be at least some reduction in risk of contracting a mosquito-borne disease (Goddard, 2008). This section will attempt to find out if this statement can be supported.

West Nile Virus is endemic in the US, where there is a significant resistance to the application of pesticides by the general public. This has led to a number of investigations into the effects of control methods on the transmission of this disease. One such study in CA, U.S.A., documented the effect of different control strategies over a 3-year period on the number of human cases. West Nile Virus initially entered the Coachella Valley, CA, U.S.A, in August 2003. In 2004 and 2005, an attempt was made to interrupt the amplification and dispersal of WNV using ground ULV applications of Pyrenone 25-5(R). Treatments were localized and started 1 month after the initial detection. Evaluations of ground trials in 2005 indicated that the ULV spray can effectively reduced the abundance of the vector mosquito. However, these reactive ground treatments appeared to have little effect on virus transmission, and WNV was eventually detected throughout the area (Lothrop *et al.*, 2007). Timely aerial ULV treatments at North Shore in 2006, however, appeared to interrupt the early season amplification, contained early dispersal of WNV. Factors contributing to the success of the aerial treatments included the ability of the aircraft to reach large acreage not accessed by road, especially the shoreline vegetation, the treatment of large acreage ahead of the dispersal track of the virus and repeated treatments. Although the calculated per cent control averaged only 61%, repeated treatments apparently compensated for gaps in coverage and missed targets. Surveillance data from control areas that did not receive adulticide treatments indicated that WNV activity was greater during 2006 than in previous years, in marked contrast to the decrease reported in the treatment site. Another study used a political ecology frame work to explore how the local politics of mosquito control affected the spread of WNV in the Chicago, IL, U.S.A, metropolitan area during the 2002 outbreak. Four separate districts were studied and the timing and dates of larvicide and space spray treatments were found to be important. The Northwest and Des Plaines Valley districts had fully operational catch basin larvicide programmes in place before 2002, as well as a greater knowledge of where catch basins were located. The North Shore and South Cook districts did not begin to larvicide until after the arrival of human WNV cases. There were vast differences in the ways the districts handled adulticiding. Northwest did it early, in June, when they first received reports of WNV-infected mosquitoes and often, Des Plaines Valley and North Shore did some, and South Cook did none until ordered by regional health authorities to do so. The adoption of vigorous and timely vector control and education policies in Northwest and Des Plaines Valley led to only 37 and 14 human cases, respectively. Whereas, North Shore had 153 and South Crook 192 human cases (Tedesco *et al.*, 2010).

Control of malaria vectors typically involves insecticide-treated nets or indoor residual spraying. These measures are particularly effective in Africa, where the major vectors are largely endophilic and endophagic. However, where the impact of ULV applications on exophilic malaria vectors has been studied the outcome has been positive. In the Miragoane Valley of Haiti a consistent pattern in the incidence of Plasmodium falciparum malaria over a 10-year period made it possible to predict an annual outbreak and perform a study to test the effects of aerial ULV malathion on epidemic levels of this disease. The first spray cycle produced a sharp and immediate drop in populations of the vector *Anopheles albimanus*, followed 4 weeks later by a decrease in the incidence of malaria throughout the valley. The incidence of malaria was similar in sprayed and unsprayed areas before the effect of ULV malathion, and it was significantly different during the subsequent 3 months (16.8 cases/month/10 000 population in sprayed areas and 65.4 in unsprayed; $P < 0.001$). Results of the previous study indicate that aerial spraying of ULV malathion can interrupt epidemic transmission of *Plasmodium falciparum* malaria by a susceptible vector (Krogstad *et al.*, 1975). No change was measured in susceptibility of the vector mosquito to malathion after six applications of spray during a period of 50 days. An ecological study revealed no significant impact on non-target vertebrates. Factors that contributed to the success of this method in Haiti were: (a) a susceptible population of mosquitoes; (b) suitable topography and climatic conditions for spraying; and (c) treatment of an area sufficiently large to minimize the influence of immigration of mosquitoes from unsprayed areas (Eliason *et al.*, 1975).

Another example is Tamil Nadu, India, which has had a high persistent transmission since 1975. The malaria incidence was reduced to one-fifth in villages under ULV malathion as against a 50% drop in the control village. Entomological studies showed that as a consequence of outdoor resting by the vector *Anopheles culicifucies,* indoor residual spraying with malathion was ineffective in malarious villages. Over a 4-year period during which residual spraying was supplemented with ground applications of malathion space spraying, the slide positivity among patients with fever fell from 21.04% to 1.1% (Tewari *et al.*, 1989).

In the case of Dengue fever and *Ae. aegypti* there is a mixed result to ULV spraying. The behaviour of this vector makes it a difficult target for space sprays. It is active during unstable to neutral conditions and at a time when the population is active also. Moreover, it is sequestered in a hard to penetrate habitat. Clark *et al.* (1989) aerially applied Dibrom 14, an organophosphate, and assessed control via indoor and outdoor mosquito bioassay cages. Indoor locations were unaffected by the spray, and oviposition was only temporarily reduced during and just after the application over five consecutive days. The problem is clearly getting the insecticide into the house. A ground ULV study that applied the chemical during peak activity at the San Juan Laboratories-Dengue (1987) showed that oviposition rates were not affected by the spray. Twenty-four-hour mortality rates generally exceeded 95% in bioassay cages placed in front yards and the roof. In back yards, sheltered sites and indoors, mortality rates variable ranged from 0 to 84%. Droplet collections and visual observations confirmed that the fumigant passed roofs, between houses and into back yards in quantities that appeared compatible with the observed bioassay kill. However, this previous study did conclude that there was some resistance to the chemical used and that the cages were not a true representations of the Aedes resting site. By constrast, bioassays with caged, laboratory-reared *Ae. aegypti* females showed that ground ULV treatments were generally effectiveeven although, survival was high in assay cages placed indoors and in other protected sites. The decline in dengue cases beginning 2 weeks after the initiation of spraying, coupled with the continued rise of cases in the rest of the island, suggest that the treatment was effective in slowing the epidemic down in the metropolitan area. However, as a variety of control measures, including public education and source reduction, were begun in the metropolitan at the time, it is not possible to definitely separate the effects of ground ULV alone. A systematic review of peridomestic space spraying was conducted by Esu *et al.* (2010) and the conclusion was that more research is needed to come to a practical public health conclusion, either to recommend or to reject the use of peridomestic space spraying for dengue vector control and to provide clear guidelines for appropriate implementation and monitoring of effect. Two of the three truck-mounted applications considered in this review concluded that the method would provide sufficient dengue control during an epidemic (Pant *et al.*, 1971, 1973). The ground ULV campaign that had no sustained effect of the Aedes populations applied the chemical after dark when the target was resting (Hudson, 1986). Out of the aerial application studies, two showed poor control and one showed effective control of the *Ae. aegypti* population.

Conclusions

Mosquito control is often highly controversial, particularly when it involves the use of pesticides or biological controls that have their own potentially serious health and environmental impacts. Local officials, activists and residents often have varying perspectives on control strategies, resulting in local 'narratives' of control (Suarez *et al.*, 2005).

During the collation of references for this review article it became apparent that most of the studies were conducted with minimal knowledge of the technology that was being employed. Little to no information was available on the two primary parameters that define spray movement; the droplet size distribution and meteorology at time of application. It should be realized that no chemical can be more effective than the application method used to apply it. If the chemical does not reach the target then it will not work.

Where the chemical is applied correctly under the required conditions, the evidence shows (a) that ULV space spraying can be effective at controlling mosquito populations; (b) that the non-target impact does not exceed levels of concern; and (c) that disease transmission can be interrupted. However, the Aedes vectors highlight how and where ULV space sprays can falter. Applications must clearly be repeated and should be conducted at the time of flight activity not on a calendar basis. The time of application, however, is challenging on a meteorological level and where conditions are not conducive to a successful application this technique will probably fail and therefore should not be used. If *Ae. aegypti* transmitted disease occurs, environmental management has obviously been inadequate and rapid measures are needed to control transmission. Space spraying is an effective tool, and should be used when appropriate meteorological conditions prevail in a holistic judicious Integrated Mosquito Management programme (Conlon, 2011).

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