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Research

Biological and Microbial Control

Toys or Tools? Utilization of Unmanned Aerial Systems in Mosquito and Vector Control Programs

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Abstract

Organized mosquito control programs (MCP) in the United States have been protecting public health since the early 1900s. These programs utilize integrated mosquito management for surveillance and control measures to enhance quality of life and protect the public from mosquito-borne diseases. Because much of the equipment and insecticides are developed for agriculture, MCP are left to innovate and adapt what is available to accomplish their core missions. Unmanned aerial systems (UAS) are one such innovation that are quickly being adopted by MCP. The advantages of UAS are no longer conjectural. In addition to locating mosquito larval habitats, UAS affords MCP real-time imagery, improved accuracy of aerial insecticide applications, mosquito larval detection and sampling. UAS are also leveraged for applying larvicides to water in habitats that range in size from multi-acre wetlands to small containers in urban settings. Employing UAS can reduce staff exposure to hazards and the impact associated with the use of heavy equipment in sensitive habitats. UAS are utilized by MCP nationally and their use will continue to increase as technology advances and regulations change. Current impediments include a dearth of major UAS manufacturers of equipment that is tailor-made for mosquito control, pesticides that are optimized for application via UAS and regulations that limit the access of UAS to national airspace. This manuscript highlights the strengths and weaknesses of UAS within MCP, provides an update on systems and methods used, and charts the future direction of UAS technology within MCP tasked with public health protection.

Key words: drone, unmanned aerial vehicle, integrated mosquito management, larvicide, adulticide, vector surveillance

Mosquitoes (Diptera: Culicidae) are the most important vectors of pathogens and arthropod-borne viruses on Earth. They have plagued humanity for centuries, crucially impacting our quality of life and causing catastrophic economic and public health losses because of their medical and veterinary implications (Philip 1973). Discovering the role of mosquitoes in the ecological and epidemiological transmission cycles focused humanities efforts toward controlling them.

The modern mosquito control movement began in New Jersey around the turn of the 20th century, largely around the efforts of John B. Smith, an attorney and self-trained entomologist. His desire for relief from mosquito bites and increased property values triggered the establishment of American mosquito control programs (MCP). Perhaps his greatest contribution stemmed from the appreciation that mosquitoes have no regard for political boundaries and his championing of legislation that authorized the formation of mosquito abatement commissions first in New Jersey during 1912, followed soon thereafter by California (1915), Utah (1923), and Florida (1925; Patterson 2009). Modern abatement efforts and organized MCP have benefited from over a century of experience.

The adoption of unmanned aerial systems (UAS), commonly known as drones, by MCP is a classic example of the industry swiftly adopting new equipment. The commercial demand for these systems and open-market competition is motivating rapid technological advances that no longer categorize UAS as toys, but rather as valuable tools that can expedite surveillance and enhance accurate mosquito control measures. Their appreciation in MCP for improving workflows is growing (Buettner and Haas-Stapleton 2020). Herein, we summarize the existing and potential future uses of UAS by MCP in the United States and abroad. We discuss current surveillance methods regarding the detection and inspection of aquatic habitats, water and larval sampling, and adult sampling; larval control measures; and adult control measures. We also discuss the advantages that UAS offer within MCP. We conclude with a broad overview highlighting the pros and cons of UAS and discuss the regulatory obstacles that are preventing this technology from truly taking off.

Surveillance

Locating Mosquito Larval Sites

The most import component of an integrated mosquito management program (IMMP) is to locate the aquatic habitats where mosquito larvae develop (Rajagopalan et al. 1990). In large rural habitats, the vast majority of modern mosquito control efforts are focused upon vast bodies of standing water such as marshes and floodwater plains (Knight et al. 2003). UAS can quickly navigate above such habitats, which often contain multiple terrestrial obstacles, to provide a bird's eye view of mosquito larval sites that would take an inspector hours to complete on foot (Chabot and Bird 2013, Haskins et al. 2021). Compared to conventional satellite or high-altitude imagery which typically offer outdated meter or greater level resolution (Zhou et al. 2018), UAS can provide real-time centimeter-level resolution (Anderson and Gaston 2013), which substantially increases the precision of MCP efforts. UAS can guide technicians to determine best water management strategies (e.g., where to drain impounded water) or where to apply target-specific larvicides that prevent mosquito larvae from developing into flying and biting adults. By focusing treatments on the obligate aquatic larval stage of mosquito development, costs and non-target impacts can be reduced and control is more effective compared to what can be achieved with wide-area dispersal of insecticides intended for adult mosquitoes. By utilizing a spatially and temporally focused approach, overall increases in environmental and public health stewardship are also realized. Therefore, locating aquatic habits is of paramount importance to MCP.

Advanced UAS are typically equipped with camera payloads that further enable the collection of enhanced or specialized imagery for locating larval sites in aquatic habitats (Anderson and Gaston 2013). Simple aerial images captured in the visible light spectrum coupled with mission-specific flights above areas of interest can identify habitats that may support mosquitoes (Case et al. 2020). Equipping UAS with a multispectral or hyperspectral camera can show inspectors if water quality is adequate for mosquito growth, vegetation type and status, pin-point exact mosquito larval habitats, and show elevation gradients that allow inspectors to predict areas that could collect water and allow mosquitoes to develop (Johnson et al. 2020). This concept is not new to MCP and has been used in precision agriculture to image the landscape and quantify vegetative indices, such as the normalized difference vegetation index (NDVI) to determine variabilities in field crops (Benincasa et al. 2018, Viljanen 2018). NDVI and other indices may be utilized to determine a variety of different vegetative conditions such as nutrient stress, water stress, plant diseases, or even predator impact (Gago 2015, Hassler et al. 2019). Other sensors and imaging devices such as simple visible spectrum cameras, high magnification zoom video cameras, and even thermal cameras are also being utilized within precision agriculture (Iost Filho et al. 2019) and are being adopted rapidly for mosquito control.

UAS are well suited for producing high resolution georectified orthomosaic maps to locate areas where water has or may accumulate after flooding, delineate accurate treatment areas, and analyze gradient or vegetated areas (Langhammer and Vacková 2018, Doughty and Cavanaugh 2019) so that best management practices can be implemented to reduce mosquito abundance (Rey et al. 2012). When it comes to aerial UAS mapping, there are two types of accuracy: relative and absolute (DroneDeploy 2017a). The former is related to the accuracy of distances between two points on a map and the real world. Absolute accuracy is related to how well latitude and longitude on a map correspond with Global Positioning System (GPS) coordinates that are collected by the UAS. Sacramento-Yolo Mosquito and Vector Control District (Sacramento County and Yolo County, CA, USA) utilized a DJI Phantom 4 Pro (P4 Pro; Table 1) with survey-quality ground control points (GCP) that were placed in the flight path provided centimeter level precision GPS coordinates in the images that were captured by the UAS (Harwin and Lucieer 2012, DroneDeploy 2017b). Although placing GCP was relatively simple if the topology of the landscape was uniform (e.g., urban setting or construction sites), doing so in wetlands was onerous. Moreover, survey-quality GCP with built-in GPS recorders such as AeroPoints cost approximately $800 USD each (Propeller Aer, CO, USA), and at least two GCP are needed per hectare to produce orthomosaic maps with high absolute accuracy (Haskins et al. 2021). Less costly GCP alternatives include large, highly visible objects such as orange traffic cones. Basic GCP must be associated with GPS coordinates using a portable high precision receiver such as the Trimble R2 which offers up to 1–2 cm precision (Trimble Inc., Sunnyvale, CA). High precision receivers are costly to purchase (approximately $13,000 USD for the Trimble R2), but MCP may be able to partner with other agencies to reduce such costs. With the release of the DJI Phantom 4 Pro RTK (P4 Pro RTK) UAS, the traditional ground control point-based method is being challenged with a potentially less expensive and faster survey method. The real-time kinematics (RTK) module of this UAS provides centimeter level positioning precision using a base station, without GCP. Instead, the P4 Pro RTK communicates with a single DJI D-RTK 2 Mobile station or utilizes a subscription-based Network Transport of RTCM via Internet Protocol such as Skylark (SwiftNavigation 2021) to obtain precise GPS coordinates for producing orthomosaic maps with centimeter precision absolute accuracy. UAS with RTK cost 50–200% more than the same model that lacks RTK, which could be a barrier to underfunded MCP. LiDAR (light detection and ranging) point clouds captured using aerial UAS can provide centimeter-level resolution topographical maps but may not accurately measure surface elevation of sloping landscapes or when dense vegetation is present. Elevation errors that result from LiDAR point clouds reflecting from vegetation in tidal marshes were reduced 40–75% using NDVI imagery that was captured with a multispectral camera (Buffington et al. 2016).

Before larvicides can be applied, the precise location of standing water must first be determined. Hence, the most pivotal aspect of UAS is the detection of larval mosquito aquatic habitats both in rural and urban/suburban habitats (Hardy 2017, Haas-Stapleton 2019, Aragao 2020, Case 2020, Schenkel 2020). This operation is much easier to complete when dealing with rural floodwater or marsh habitats that are often large, semiaccessible, and in open

Table 1. Specifications of UAS used for mosquito control (DJI 2021, LEAT 2021, SwellPro 2021)

	Weight (kg)	Diagonal distance (mm)	Flight duration (min)	Built-in camera resolution	Built-in camera maximum zoom	Notes	Approximate base price (USD)
Surveillance							
DJI Mini 2	0.25	213	31	12MP	2×		$450*
DJI Mavic 2 Zoom	0.9	354	31	48MP	4×	4K video	$1,350
DJI Phantom 4 Pro 2	1.4	350	30	20MP	0×	4K video	$1,600
DJI Mavic 2 Advanced	0.9	354	31	48 MP + Thermal	32×	4K video; Optional RTK, spotlight, beacon and speaker accessories	$6,500*
DJ P4 Multispectral	1.5	350	27	2MP multispectral	0×	RTK positioning; multispectral camera; 0.63 km^2 single flight mapping	$6,500
DJI Matrice 300	6.3	895	55	960p	0×	RTK positioning; Water resistant; Multiple cameras; Enhanced airsense awareness; Optional radar	$6,500
SwellPro Spash Drone 3+	2	450	23	not included	N/A	Floats on water and waterproof; 1 camera payload (4 options); optional payload release system	$1,200*
Insecticide application							
DJI AGRAS MG-1P	23.8	1,500	12 (full pesticide load)	960p	0×	Ground avoidance radar; Water resistant; Included spray and optional granular module; Optional RTK	$14,000*
Spreading Wings S1000+	7.3	1,045	20	not included	N/A	Flexible payload platform for camera or insecticide application	$5,800
PV 22	27	1,800	16	720p	N/A	16-liter spray tank or 18-liter granular hopper	$18,000
PV 35	35.8	1,980	16	1,080p	N/A	16-liter spray tank or 20-liter granular hopper; Terrain and obstacle avoidance; Optional RTK	$25,000

An asterisk indicates that the base price includes a UAS controller.

public lands. But the process is much more difficult for peridomestic mosquitoes that thrive in small artificial container habitats, which are small, ubiquitous, difficult to access, and primarily in residential or private backyards. The precision of pesticide applications in such disparate mosquito management unit sizes can improve if UAS are employed. For example, a UAS outfitted with a multispectral camera was employed to locate and quantify accumulated surface water on a tidal marsh, leading to focused water management efforts that reduced impounded water and precise inspections for larval control by ground crews (Haas-Stapleton et al. 2019). UAS fitted with a high-magnification zoom video camera visualized mosquito larvae inside artificial containers that were placed within a marsh at heights of up to 14 m (Haas-Stapleton 2019). An artificial intelligence algorithm applied to those images simplified the process of quantifying mosquito larvae in these artificial containers, showing promise for rapid field enumeration of juvenile mosquitoes within aquatic habitats (Haas-Stapleton 2019).

Detecting mosquito larval habitats in geographically smaller peridomestic environments is much more challenging for several reasons. Aquatic habitats in urban environments may not reoccur in the same area or be delineated like aquatic habitats within rural areas that are often predictable and recurring. Additionally, in rural habitats, the primary mosquito species (*Aedes sollicitans* Walker, *Aedes taeniorhynchus* Wiedemann, *Aedes vexans* Meigen, and *Culex tarsalis* Coquillett) occur in large broods following rain, floods, or tidal swells, which allows for concerted control efforts following these predictable events. In contrast, urban mosquito control is often geared toward species that develop in relatively small water-holding containers such as *Aedes aegypti* Linnaeus, *Aedes albopictus* Skuse, and *Culex pipiens* Linnaeus. These containers, such as tires, buckets, flower pots, or trash, are ubiquitous and reoccur intermittently within peridomestic environments (Faraji and Unlu 2016). Detecting these habitats is extremely difficult, not only because of their pervasiveness, but also because they are often cryptic and on private property that cannot be accessed by MCP personnel (Unlu 2013, 2014). Nonetheless, some researchers are utilizing UAS to survey potential mosquito larval habitats even within urban and suburban environments. For example, Case et al. (2020) demonstrated that a convolutional neural network exploiting UAS images can detect *Ae. albopictus* habitat in suburban communities and that the number of containers imaged by the UAS could predict the number of containers positive for mosquito larvae in each home. Their neural network was able to identify most of the potential habitat, and could classify whole properties as positive or negative for mosquito larvae in 80% of the cases (Case 2020). A mathematical model was developed to identify technical features of a UAS that are most important for efficient aerial mapping of sites that can support *Ae. aegypti* mosquitoes (Aragao 2020). Furthermore, Suduwella et al. (2017) conducted experiments using UAS in Sri Lanka to locate aquatic habitats with visible lichens in inaccessible areas such as roof gutters and overhead water tanks that were indicative of prolonged standing water and thus provided ideal mosquito larval habitat. Other researchers in Brazil used computer vision tools from UAS aerial images and machine learning to detect large artificial containers such as abandoned tires and small pools of stagnant water utilized by *Ae. aegypti*, the primary vector of dengue virus in that region (Dias 2018). Engaging artificial intelligence algorithms to locate mosquito larvae and pupae in peridomestic containers has tremendous potential in the future for locating and controlling *Ae. aegypti* in urban and suburban habitats. In addition to two-dimensional imagery, most UAS and associated software can be used to produce three-dimensional (3D) images of objects that are not obstructed. Such 3D images may be invaluable when surveying for artificial container habitats in peridomestic areas. For example, a 3D survey of a junk yard or automotive mechanic shops with large piles of tires and/or other artificial containers may provide essential information on volume or area (Case et al. 2020). These criteria are extremely important when determining which pesticide product or formulation to utilize, in addition to determining application rates for economic, environmental, and legal compliance. The rapid advances of UAS for detecting water, containers, and surveying other inaccessible or cryptic habitats within urban environments, in addition to the identification and enumeration of mosquito juveniles, provides tremendous potential for MCP globally.

Much of the surveillance efforts for water, containers, and larvae were conducted using commercially available UAS in the USA. A partial list of the most commonly used UAS units within MCP in the USA is provided in Table 1. The vast majority of UAS are manufactured by SZ DJI Technology Co., Ltd. (Shenzhen, China). The technological advances, reliability, affordability, and user friendliness of these UAS have quickly established them as the gold standard for existing and rising programs. The four-rotor DJI UAS that have been used by MCP for surveying habitats range in diameter from a little over 100 cm to nearly a meter and weigh as little as 249 g to upwards of 6 kg. The smaller UAS come equipped with integrated 12–20 megapixel cameras that capture still images or video in the visible spectrum. The larger UAS typically carry more advanced instrumentation such as thermal infrared, multispectral and/or high magnification zoom cameras that on some UAS are modular and may be equipped with additional sensors that enable centimeter-level precision in piloting and image geocoding. Flight duration is determined primarily by the weight of the UAS and battery capacity. Small to mid-sized UAS such as the DJI Mavic Mini 2 and P4 Pro 2 are lightweight but cannot carry large batteries and are thus limited to flight durations of around 30 min under optimal conditions. Task specific UAS such as the DJI P4 Multispectral is essentially a DJI P4 Pro equipped with RTK and a multispectral camera with six sensors that capture images in the blue, green, red, red edge, and near-infrared spectra. Larger UAS such as the DJI Matrice 300 can stay aloft for nearly an hour and carry up to three payloads (e.g., LiDAR, multispectral, thermal, and zoom visual wavelength cameras). The cost for simplest UAS that has been employed by MCP for surveillance is a modest $450 USD (DJI Mini 2), while the more advanced systems exceed $10,000 USD if specialized instruments or additional flight batteries are included. Most of these UAS surveillance units are considered reasonably priced for established MCP in the USA and require relatively little investment and time in order to be incorporated into an existing IMMP.

Water and Larval Sampling

The advantages of using UAS to detect larval habitats and mosquito larvae are evident, but it would be ideal to collect samples so that the water quality and mosquito species could be assessed directly. Unlike agriculture, mosquito control is a niche market with a dearth of commercially available products for collecting such specimens using a UAS. Most MCP are fortunate to employ dedicated individuals that are proficient fabricators and tinkerers who routinely develop new tools and techniques to increase efficiency and efficacy. This necessity has led to innovations for the betterment of public health and society.

Lee County Mosquito/Hyacinth Control District (FL, USA) personnel modified a standard SwellPro Splash Drone 3+ (SwellPro, Shenzhen, China) to serve as a water sampling UAS for their inspections (Fig. 1A). This UAS is a waterproof quadcopter and is typically used recreationally around large bodies of water for filming, fishing, or boating. They fabricated additional leg supports and a water sampler holder for the UAS to collect aquatic samples from the various habitats that they must monitor (Fig. 1B and C). The modifications allow the Splash Drone 3+ to hold either a 250 ml or 500 ml plastic vial with relative ease. When this buoyant UAS landed on top of inaccessible aquatic habitats, the vial became submerged to fill with water. They returned the UAS to the launch site to retrieve the sample. This has allowed for the collection of water samples in a matter of minutes from the field in hard-to-reach areas that would take technicians hours to complete from the ground. UAS were shown previously to facilitate microorganism collections from a lake; however, a long tether was utilized to lower the sample reservoir into the water column (Benson 2019).

Another example of a modified UAS for water and larval sampling was made by the Hudson Regional Health Commission (Hudson RHC, NJ, USA). They modified a DJI P4 Pro and fitted it with a float and a pump to collect mosquito larvae (Fig. 2). The UAS lands on the water, motors are disarmed, and the pilot activates a siphon water pump to collect a water sample into a screened vial by turning off the navigation lights. Mosquito larvae are trapped in the vial by the screen as excess water flows out. Because the pump flows at a consistent 1 liter/min, known volumes of water can be sampled. To stop the pump, the navigation lights are turned back on and the pilot can arm the motors and return to the launch site.

Locating aquatic habitats and mosquito larvae, and monitoring water quality with UAS should be coordinated with mosquito control interventions. Ideally, the subsequent treatment applications could be conducted by control UAS optimized for pesticide applications. If the insecticide is not applied using UAS, surveillance UAS can provide detailed aerial imagery and data for optimizing treatment blocks that is utilized by ground crews or larger manned aircraft. Regardless, with the increasing adoption of UAS as surveillance tools within MCP globally, the profession will undoubtedly drive additional developments and technological advances to streamline and standardize the process of water or larval collections from a range of aquatic habitats.

Adult Mosquito Surveillance

Adult mosquitoes have several life processes that are exploited for surveillance to determine presence, abundance, pathogen infection rates, and ultimately, risk assessment for protection of veterinary and public health. To summarize, adult mosquitoes first emerge from the aquatic pupal stage, both sexes seek dietary carbohydrates typically from plants to support the high energy requirements of flight and other biochemical demands (Yuval 1992), they seek shelter in high humidity environments and mate (Clements 1999), the females seek a bloodmeal for egg development, rest to digest the blood (typically among vegetation), and a few days later the females oviposit the eggs in a suitable aquatic habitat. If fortunate, she will repeat

Fig. 2. Larva sampler UAS. Photo courtesy of Hudson Regional Health Commission (NJ, USA).

Fig. 1. A commercially available waterproof quadcopter. SwellPro Splash Drone 3+ (A) has been modified to obtain water samples from aquatic habitats for environmental monitoring (B, C). Top photo courtesy of SwellPro (https://www.swellpro.com), bottom two photos courtesy of Lee County Mosquito/Hyacinth Control District (FL, USA).

the entire process several times over the course of weeks or months. Appreciating the biology and ecology of each species is crucial for successful mosquito control. Detecting healthy vegetation used by adult mosquitoes for resting and sugar feeding is crucial for successful adult surveillance and control efforts. Moreover, mosquitoes may mate within large aerial swarms and use environmental cues such as bushes or treetops to locate mating swarm sites (Clements 1999). Locating swarm sites using UAS aerial imagery could lead to more precise pesticide applications. All of the above can be accomplished by using the same UAS noted above for larval habitat monitoring (Table 1).

UAS may also be used by MCP to identify environmental conditions that are optimal for localized mosquito diel flight activity and the altitude at which mosquitoes fly so that they can be more efficiently controlled with adulticide applications. This is particularly important when conducting adulticide sprays through cold aerosol ultra-low volume applications either with truck-mounted or aerial equipment. Adulticide applications are generally conducted during the night time after a thermal inversion has been recorded, temperatures are above 10°C, and a light breeze above 1.6 km/h but below 16 km/h is present (Faraji et al. 2016). Most MCP rely upon existing weather stations, erect portable weather station towers, or utilize weather balloons to record essential meteorological data (Mount 1998). However, these methods may be cumbersome, unreliable at times, or may not be located within the specific spray block. As a result, UAS with built in weather monitoring equipment for humidity, temperature, wind speed and direction, could be used effectively within the actual spray area, at the appropriate times, to provide real-time information prior to an adulticide application (Palomaki et al. 2017). Temperature recordings could also be conducted at the ground level, in addition to various heights using UAS to determine if a thermal inversion has occurred. Such data would provide the pesticide applicators timely and accurate data so that real time adjustments could be made to the spray equipment or method to limit pesticide drift, which would in turn increase treatment efficacy and environmental stewardship.

Additional Surveillance Uses

There are several other projects underway to further enhance the capabilities and value of UAS within IMMP. For example, within urban habitats, UAS technologies can access abandoned industrial buildings deemed unsafe for humans or large junkyard or tire piles too difficult for ground-based surveillance. These habitats pose great risk for human inspectors to access or sample, and yet are prolific mosquito production sites that must be examined and treated regularly. Sophisticated UAS with obstacle avoidance technology can be remotely deployed and effectively navigate, photograph, map, or sample these habitats with relative ease. Small UAS can also quickly map areas of concern and yield accurate aerial spray blocks that can thereafter be distributed with fine detail to larger manned aerial application equipment for treatments.

Another natural progression for MCP is to monitor adult mosquito abundance with traps that are integrated into UAS for use in hard-to-reach or remote habitats, abandoned industrial complexes, or even high up in tree canopies. Standard mosquito traps used by MCP often utilize a lure (carbon dioxide or a chemical lure such as octenol) or light source to attract mosquitoes (Kline 2007) to a suction fan that deposits the mosquitoes into a container. UAS have the power and circuitry already built in that can be used to power and control a mosquito trap. If supplementary power is needed, UAS could be fitted with small solar panels to maintain or charge the batteries needed to power such traps. Regardless of the specific technology, the future looks bright for the incorporation of UAS for surveillance of mosquitoes and mosquito-borne pathogens within IMMP worldwide.

Control

Larval Control

There is no doubt that UAS used for surveillance are probably the biggest value and initial use for most MCP. However, the next natural progression is to utilize UAS for actual control applications. Larval control measures are a key workhorse of any IMMP and the methods and process, although constantly evolving, have been fine tuned for over a century now. Incorporating UAS technology for larval control purposes is another natural progression for MCP and one that may reap many benefits. Larval control using UAS provides additional advantages that are not afforded by traditional larviciding measures. Some of these benefits include the ability to conduct precision larval control through designing much smaller treatment blocks or point applications leading to reduced pesticide usage and treating areas close to sensitive areas where manned equipment may not be permitted access. Use of UAS for mosquito control may reduce the ecological footprint via reduced disturbance of wildlife, terrestrial impacts (e.g., vehicle tracks), and transport of invasive organisms from one habitat to another. Cleaning UAS after applications is also simplified, as little mud or debris is taken up by the equipment. The relatively small payload and short flight time of current UAS reduce their utility for larvicide applications over large geographic areas; this limitation is generally offset by the greater precision that UAS offer.

Larval Control—Liquid Applications

Liquid applications of larvicides are considered the most economical form of aerial pesticide applications for mosquito control. The active ingredients are often similar to granular or tablet formulations, however, the real advantage is in the ability to dilute these products with water to adjust application rates and modify delivery of the product under different environmental or habitat conditions. Most of these formulations are commercially available in a liquid format, wettable powders, emulsified concentrates, or water-dispersible granules that are mixed with water. While liquid applications can be more economical, they do exhibit certain limitations. Some of these include the need to apply the product quickly after mixing so that the active ingredient remains efficacious. Drift and penetration of the product into the larval habitat are also difficult to accomplish under certain conditions. Liquid droplets are more susceptible to wind dispersal and propeller wash vortices. Additionally, liquid droplets may not efficiently enter water that is sheltered by dense or tall vegetation because the droplets adhere to the leaves and branches.

Although there are now commercial UAS that can apply mosquito control products, most MCP initially modified surveillance UAS so they could apply insecticide. Perhaps the most characteristic example is an eight rotor DJI Spreading Wings S1000+ modified for liquid larvicide applications by incorporating 3D-printed components, such as a quick-detach custom baseplate for mounting and swapping spray systems (Fig. 3A). For the spray system, they exploited over the counter products, adapting a similar design intended for agricultural applications (Huang 2009, 2015). This unit was reported to fly for over 20 min with all accessories and was able to cover an application area corresponding to 8.5 ha with a single battery (Williams 2020). Since the demand for liquid pesticide

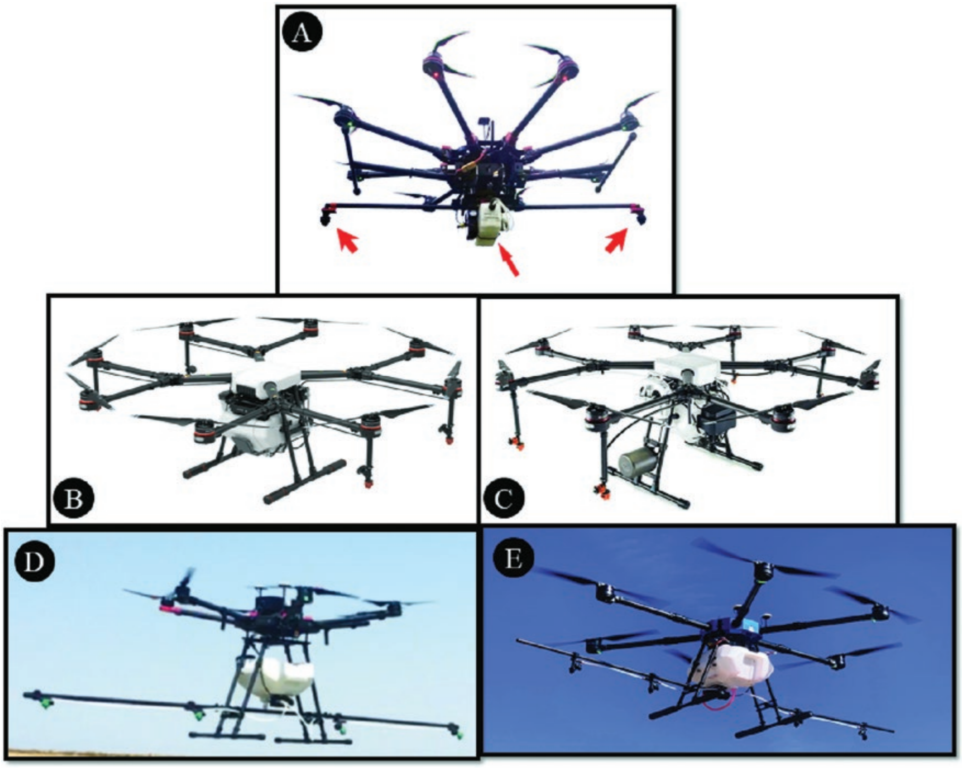

Fig. 3. Liquid larvicide UAS platforms used for mosquito control. Top photo (A) depicts an in-house fabricated unit by the Hudson Regional Health Commission (NJ, USA). The unit was built on the DJI Spreading Wings S1000+ platform. Arrows indicate the spray tank and two nozzles on the ends of the spray boom. The middle two photos depict the commercially available units from DJI, the MG-1S (B) and the MG-1P (C). The bottom three photos depict commercially available UAS sprayer units from Leading Edge Aerial Technologies, the PV-22 (D), and PV-35 (E). Detailed information found within text. Top photo courtesy of Hudson Regional Health Commission, middle photos courtesy of SZ DJI Technology Company (https://www.dji.com), bottom photos courtesy of Leading Edge Aerial Technologies (https://leaaerialtech.com).

applications via UAS is growing globally, DJI currently offers several UAS that apply pesticides for the crop protection. These include the eight rotor DJI Agras MG-1S and the updated DJI MG-1P (Table 1, Fig. 3B and C). The DJI Agras line has been a true workhorse model for MCP in recent years. Although the MG-1S is being phased out by DJI, fully prepped spray models can still be purchased for around $7,500 USD.

Leading Edge Aerial Technologies (New Smyrna Beach, FL), which primarily caters to the mosquito control industry, also provides several turnkey UAS for insecticide applications. These include the four rotor PrecisionVision (PV) 22 and the six rotor PV 35 (Table 1; Fig. 3D and E). All of their UAS have been designed with versatility in mind, and the process of swapping modules for liquid, granular, and ULV adulticide applications is very streamlined.

Larval Control—Granular Applications

Although liquid applications of larvicides may be the most economic method for aerial larval control, the most widely used method by MCP is by far granular applications. Solid granules behave much more predictably, are heavier, and can penetrate through dense vegetation to deliver the active ingredient to the water. Additionally, different granule formulations can be applied directly to the water or used prior to flooding or rain events to pre-treat a site. And unlike most liquid formulations, granule formulations can have an extended release or residual activity, eliminating the need for multiple treatments. Multiple active ingredients can be contained in the same granule, targeting different life stages or extending efficacy. Calibration and cleaning of spray equipment is much easier to accomplish with solid granules. Because most agricultural crop protection sprays are liquid applications, there are limited options for granular application using UAS that are available for mosquito and vector control. Thus, the early adopters of UAS for mosquito replied upon in-house expertise to modify existing equipment to produce a granular spreader. An early innovation was to augment a hand-operated granular spreader with an electronic gear motor using 3D-printed components to actuate the trigger controlling the hopper flow gate (Fig. 4A). The flight control software was used to regulate impeller speed and hopper flow to maintain a consistent application rate based on the speed of the UAS. The hopper had a volume of 2. 9 liters and could hold 1.1–2.8 kg of the most commonly used granular insecticides for mosquito control (Williams 2020). These volumes are sufficient to treat 0.3 to 1 ha of mosquito habitat at the minimum application rates stipulated on pesticide labels. A single battery could support up to two granular application missions, covering an area of over 1.5 ha. The entire cost of constructing the granule spreader for the UAS was less than $150 USD (Williams 2020).

Other modifications for granular sprayers have been undertaken at other MCP in recent years. The Salt Lake City Mosquito Abatement District (UT, USA) modified an eight rotor DJI Agras MG-1S UAS so that it could apply granular larvicide instead of liquid (Fig. 4B). Kydex thermoplastic sheeting (Sekisui, Bloomsburg, PA) was utilized to fabricate the granular hopper and an aluminum frame was manufactured to provide a quick-release mounting surface and additional strength to the hopper. The bottom of the hopper was 3D printed with mounts for an actuator to control the granular flow gate and a motor to spin the disk that spread

Fig. 4. Granular larvicide UAS platforms used for mosquito control. Top left photo (A) depicts an in-house fabricated unit by the Hudson Regional Health Commission (NJ, USA). The unit was built on the DJI Spreading Wings S1000+ platform. Top right photo (B) depicts an in-house fabricated unit by the Salt Lake City Mosquito Abatement District (UT, USA). The unit was built for the DJI Agras MG-1S aircraft. The middle three photos depict commercially available units with granular spreaders, including the DJI MG-1S (C), DJI MG-1P (D), and the Precision Vision line of aircraft. The bottom row depicts commercially available granular spreaders that can be purchased separately for UAS, including the DJI Agras MG Spreading System (F). Three granular hopper systems from CFR-Innovations are also shown, including the UGS-2G (G), UGS-4G (H), and the UGS-8G. Detailed information found within text. Photo A courtesy of Hudson Regional Health Commission, photos B and C courtesy of the Salt Lake City Mosquito Abatement District, photos D and F courtesy of SZ DJI Technology Company (https://www.dji.com), photo E courtesy of Leading Edge Aerial Technologies (https://leaaerialtech.com), photos G, H, and I courtesy of CFR-I (https://www.cfr-innovations.com).

the granules. An interchangeable gate restrictor was included for adjusting the flow rate using interchangeable restrictor plates with different sized openings. An electronics board was added to provide digital signals to the MG-1S platform, simulating that the now nonexistent liquid application system was still operating normally. Without these signals being supplied to the aircraft, the autonomous spray functions would cease to operate. The hopper carried 6.8–8.2 kg of the most commonly used granular insecticides. These volumes of insecticide were sufficient to treat 1.0–1.4 ha of habitat. Using a swath width of 6 m, the aircraft was set to operate at a speed of 6.7 m/s at a height of 6 m which afforded two missions per battery and treatment of up to 2.5 ha. The previous two examples demonstrate the need for MCP to develop tools and methods to increase efficacy and efficiency. It is also refreshing to note that the commercial sector is also making modifications to streamline this process for all MCP, regardless of individual capabilities within each program.

DJI now offers the Agras MG Spreading System for granular applications of pesticides that is compatible with their MG-1S and MG-1P UAS (Fig. 4C and D). It can be purchased directly with the Agras UAS or separately as an after-market add on (approximately $750 USD). This spreader weighs about 1.8 kg with a hopper volume of 13 liters and a maximum load weight of 10 kg. The hopper can disperse granular materials ranging in diameter from 0.5 to 5 mm with a spreading range of 4–6 m (Fig. 4F). Pesticide delivery rate is precisely controlled by a built-in stirring device and the hopper gate, which ensures the product does not clog and improves spray accuracy. The hopper outlet size and spinner disk rotating speed can be controlled through the software to adjust application rates. Additionally, users will be provided a notification if the hopper tank is empty, or for other abnormalities in rotating disk speed, hopper outlet size, or even temperature. All of these features make integration of the DJI Agras MG Spreading System a seamless process for granular application of mosquito larvicides.

DJI is not the only company that offers out of the box spreader solutions for granular applications. PrecisionVision UAS also offer granular application options (Fig. 4E). Each of their granule hoppers can disperse multiple materials ranging from pesticides infused on corn cob, to small pellets and sand granules. The application flow rates are adjusted with an independent variable flow controller that regulates the flow of granules based on an adjustable piston position. Swath width is controlled by a pilot-adjustable electronic speed controller. Spray on/off, aircraft speed, altitude, heading, and application rate are all controlled autonomously with the with their proprietary UAS software.

Although it is quite convenient to purchase a UAS with a granular spreader, many MCP may not wish to make an investment in a ready to go unit, particularly if they already own a UAS that lacks a spreader. As a result, adding an after-market granule spreader to a UAS is quite appealing. The DJI Agras MG Spreading System has quickly become a viable option for MCP already possessing aircraft that could accommodate that spreader (Fig. 4F). However, other options are available to increase versatility and compatibility with all types and sizes of UAS. For example, CFR-Innovations (Quebec, Canada) manufactures several granular hopper systems that have been designed for use with UAS. These include the UGS-2G UGS-4G and UGS-8G which retail for approximately $2,700–$4,000 USD each (Fig. 4G–I). Tank volumes of 8, 16, or 30 liters provide MCP a range of options to fit their current UAS. The commercial availability of after-market spreaders is making granular application of mosquito larvicides much easier to accomplish by MCP everywhere.

Larval Control—Tablet Applications

Tablet formulations of mosquito larvicides are similar to granular forms in regard to a solid formulation being dispensed for larval control. However, the main difference between tablet and granular formulations is that the former is much larger in size and are generally applied by hand rather than mechanized equipment. Sites that are ideal for treating with tablets include urban habitats with abandoned swimming pools, ornamental ponds, catch basins, tree holes, animal watering troughs, rain barrels, or other container habitats that cannot be removed or covered. Although tablets offer extended efficacy and lead to cost and time savings through reducing repeated inspections and treatments, their application is often laborious and time consuming as each must be placed by hand in each habitat. Utilizing UAS for tablet applications offers new possibilities for mosquito control.

Less research has been conducted in testing UAS for tablet applications. Once again, the Hudson RHC has taken this challenge upon themselves and have worked on two options for a tablet dropper. They used a 3D printer to manufacture a tablet dispenser module that was easily attached to a DJI P4 Pro without interfering with flight and functionality (Fig. 5A). The dispenser weighed 216 g and when filled with 15 Natular T30 tablets (Clarke Mosquito Control Products, Roselle, IL), the UAS remained airborne for approximately 20 min. That tablet applicator cost less than $100 USD to fabricate. They manufactured a second tablet applicator for the DJI Spreading Wings S1000+ UAS (Fig. 5B). This applicator was 3D-printed using acrylonitrile butadiene styrene plastic and consisted of an outer shell and an inner carousel that held eight extended release Natular XRT tablets (Clarke Mosquito Control Products, Roselle, IL). This unit cost approximately $75 to produce. Field tests showed that when the DJI Spreading Wings S1000+ UAS was piloted 4 m above the ground at 2.2 m/s, it consistently dispensed the tablet within 1.1 m of the target site (Williams 2020). We encourage private industry to produce tablet applicators for UAS so that MCP without staff expertise or equipment for 3D printing can add such capabilities to their UAS fleet.

Fig. 5. Tablet dropper larvicide module. The top left unit (A) was built for the DJI P4 Pro platform. Top right photo (B) depicts an in-house fabricated table dropped unit that could be fitted to any medium to large sized UAS platform. Photos courtesy of Hudson Regional Health Commission (NJ, USA).

Adult Control—Residual Barrier and Ultra-low Volume (ULV) Sprays

Adult mosquito control using insecticides, commonly referred to as adulticides, are often a last option available to quickly reduce biting populations of mosquitoes to improve quality of life standards and protect public health. Cold aerosol ULV or low volume residual sprays are typically applied using backpack mist blowers, truck-mounted equipment or manned aircraft. These types of applications can be made using UAS.

Low-volume liquid applications of adulticides via UAS are perhaps the easiest to accomplish among the two types. These spray applications can be readily conducted using UAS equipped for liquid larval applications (Fig. 3). Applicators could simply re-use the same tank on larvicide UAS or obtain auxiliary tanks that could be swapped out between larvicide and adulticide formulations. These already equipped UAS could be used to conduct surface sprays in areas that are difficult to access or carry traditional equipment into. This method opens a wealth of other possibilities for surface applications, such as rooftops and canopy vegetation. UAS could quickly treat tops of gazebos, arbors, military tents, and entire indoor/outdoor surfaces of huts and small homes where adult mosquitoes may congregate.

Cold aerosol ULV sprays must produce billions of pesticide droplets through a high pressure system that are small and light enough to stay aloft in the air column and contact adult mosquitoes while in flight or resting on surfaces (Mount et al. 1998). These droplets are below 50 µm size, as stipulated by federal pesticide label requirements. Fortunately, some progress has been made for ULV application of adulticides via UAS in recent years and operational options exist for MCP. For example, a electric powered handheld adulticide ULV mister (3600E, Shenzhen Longray Technology Co., Ltd., Shenzhen, China)) was adapted for use with a DJI Spreading Wings S1000+ UAS (Fig. 6). The researchers modified and fitted a small handheld electronic ULV sprayer (3600E, Shenzhen Longray Technology Co., Ltd., Shenzhen, China) onto their UAS unit (Fig. 6A). When piloted at an altitude of 6 m and a speed of 3.3 m/sec, droplet sizes of 16.2 and 22.7 µm with a droplet density of 2.6 drops/mm^2 were produced (Williams 2020), which was within federal requirements and sufficient for an efficacious ULV application. Flight time for the UAS was approximately 16 min, which could treat up to 1.8 ha on a single battery. The overall cost of this ULV spray unit, including modifications, was a little over $1,000 USD, but it offers

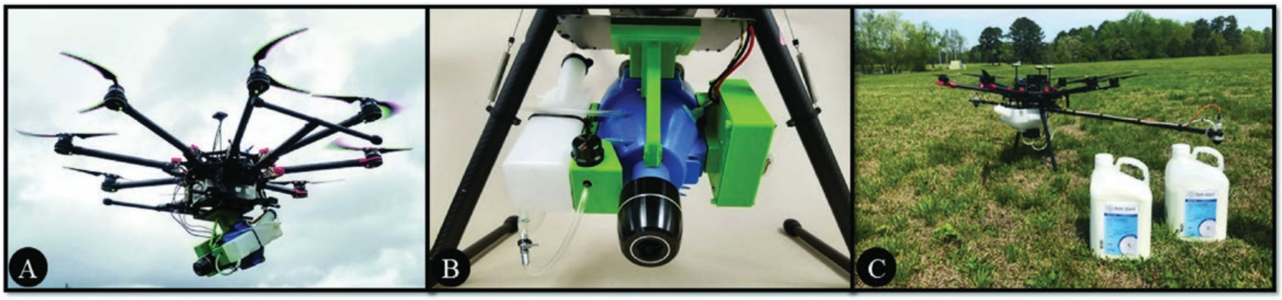

Fig. 6. Cold aerosol ultra-low volume adulticide sprayers for UAS. Left photo depicts an in-house fabricated adulticide ULV sprayer (A). Middle photo (B) depicts a closeup view of the ULV sprayer, with multiple 3D-printed components on a module that can be mounted to virtually any large sized UAS. Right photo depicts the Precision Vision line of UAS aircraft (C). These UAS come equipped with the PrecisionVision ULV Adulticiding System and are the first commercially available units for adult mosquito control. A and B photos courtesy of Hudson Regional Health Commission (NJ, USA), photo C courtesy of Leading Edge Aerial Technologies.

MCP a modular option for adding an adulticide component to their UAS operations. Regrettably, only a single commercial option for an ULV-enabled UAS exists at this time: the PrecisionVision (Fig. 6C). With the flow rate set between 30 and 90 ml/min, 40 µm diameter droplets were produced and 243 ha were treated during a single flight while flying at 8.5 m/sec (Zhai et al. 2019).

Although the overall acreage and effective swath of UAS may not compare to the area-wide capabilities of manned aircraft, they nonetheless provide a niche option that may not be available through traditional methods. Adulticide applications using manned aircraft are made at relatively high altitudes and thus must produce larger droplet sizes at the nozzle so that they are the correct size after evaporation while drifting to the ground. Applications via UAS are made at much lower altitudes, resulting in less product evaporating before it enters areas that the mosquitoes occupy. Consequently, larger volumes of pesticide must be applied from manned aircraft relative to UAS, resulting in a higher cost for materials. Manned aircraft are expensive to purchase and maintain or hire, and have minimum acreage requirements for adulticide applications (often several hundred acres). Urban applications in residential or industrial areas could be conducted with precision using UAS, instead of broad area-wide applications via manned aircraft, leading to a reduction of insecticide use with economic and environmental health benefits.

Adult Control—Genetic Control Tools

In recent years, alternative adult control methods have been gaining in academic and operational interest. Although traditional mosquito control methods described herein remain the primary tools used to combat mosquitoes and mosquito-borne diseases, there is no question that alternative control methods will only gain in usage in the coming years. For brevity, we have included multiple strategies under the genetic control tool category, but the primary message is that these alternative control tools generally accomplish abatement through the introduction of a heritable trait or gene into the target population. Some of these methods include the sterile insect technique (SIT), a variation of SIT called the release of insects carrying a dominant lethal gene (RIDL), *Wolbachia*-induced cytoplasmic compatibility, gene-silencing mechanisms achieved through RNA interference, or other selfish gene mechanisms that can disperse through insect populations quickly and cause disruptions, sterility, or mortality (Faraji and Unlu 2016). We have included these methods under adult control of mosquitoes because most of these methods will require the release of adult mosquitoes that are either sterile or carry the lethal gene of choice.

The delivery of sterile codling moths in apple orchards via UAS has already been proven in the United States, Canada, and New Zealand (Iost Filho 2020). Therefore, it is only a matter of time before this technology is used for mosquito control purposes. In fact, preliminary trials are already underway in South America for a 'drone-based aerial release mechanism for mosquitoes' (We Robotics 2018). Researchers in that region developed a canister mechanism that was attached to a UAS for transporting approximately 50,000 individual mosquitoes. Their target release rate was 2,000–6,000 mosquitoes per hectare, at a release height of 100 m, and aircraft speed of 2.5 m/s (We Robotics 2018). This method of release may prove beneficial in both rural and urban habitats, as precision release of adult mosquitoes could be conducted in inaccessible or sensitive habitats with relative ease. In rural habitats, adult mosquitoes could be released in the most optimal locations where mating swarms are most likely to occur. In urban habitats, particularly when combating invasive mosquito species, SIT releases could be conducted randomly within a grid using a network of UAS, or strategic releases could be preprogrammed for hot spots. Notwithstanding, the next phase of development should concentrate on safe and efficient means of release that could reduce transport mortality and preserve fecundity of the released insects. Although the idea of SIT release via UAS for mosquito control may be conjectural at the surface, the technique is being evaluated in Singapore using *Wolbachia* against *Ae. aegypti*, the primary vector of dengue virus in that region (NEA 2020), and using a traditional SIT approach for the same species in Brazil (We Robotics 2018).

Other Benefits and Future Direction

There are multiple benefits that UAS offer MCP everywhere. Some of these include the obvious advantages relative to mosquito control using manned aircraft: low elevation, high-resolution mapping, speed, efficiency and ease of use, increased safety to pilots, precision larval and adult control, relatively low purchase and maintenance costs, and reduced environmental impact, among others (Fig. 7). Limitations include the following: short flight times, low cargo capacity for pesticides and sensor payloads, public perception of privacy around government use of UAS, regulatory constraints.

The current rapid pace of innovation in UAS technologies brings increasingly capable UAS to the market, which may for the short term reduce the motivation of MCP to invest in transitioning traditional equipment to UAS. Higher capacity flight batteries translate to extended flight times and payload capacity. Revisions to airframe designs that have increased aerodynamics and reduce overall mass

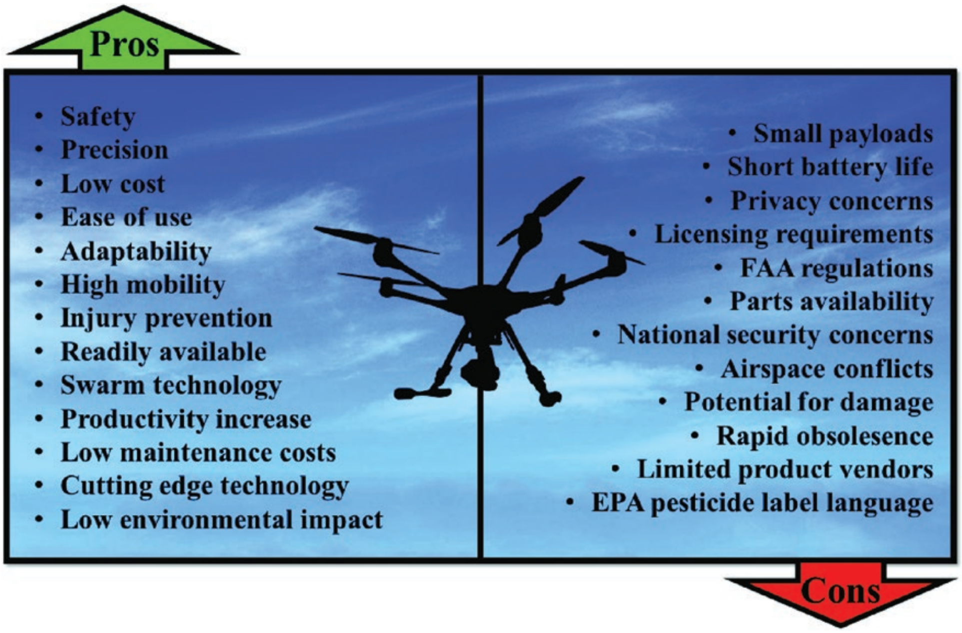

Fig. 7. Conceptual drawing of the benefits and drawbacks of UAS platforms for mosquito and vector control.

with materials that increase resilience to impact damage have concomitantly brought obvious improvements to UAS. We encourage the development of UAS fleets that are placed throughout a MCP's jurisdiction and operate semi-autonomously to monitor habitats and apply insecticide when warranted. UAS landing pads with integrated battery chargers already exist (SkyCharge 2020), and this idea could be further enhanced by automated insecticide filling stations (Stocklin 2017). Swarms of UAS operating in concert have the potential to blur lines of what can be accomplished using traditional approaches and UAS (Hunsaker 2015). The US Federal Aviation Administration (FAA) has recently offered limited approval for the experimental use of UAS swarms to reforest burned areas (Gabbert 2020). Such approvals may become more common if swarms are proven safe to operate and as technologies mature that enable parcel carriage via UAS. Challenges remain around integrating disparate technologies to achieve semi-autonomous mosquito control using UAS but are not insurmountable considering recent advancements and motivation by MCP. However, many MCP will likely continue to rely upon manned vehicles and boots-on-the-ground approaches for the bulk of their efforts until UAS technologies are more matured and the lifecycle of airframes is extended.

Current larvicides are not optimal for use in UAS because they were formulated for application by hand, manned aircraft or via terrestrial vehicles that can accommodate weighty payloads. Their use in UAS is constrained because the inactive ingredients are heavy (e.g., sand) or bulky (e.g., ground corn cob). Liquid larvicides have greater immediate use as they can be applied at low altitudes via UAS as a concentrate using low-volume atomizers. Liquid larvicide applications to heavily vegetated habitats that are common in wetlands may not prove efficacious as the liquid may coat foliage and not penetrate the water where mosquitoes reproduce. We highly encourage pesticide manufacturers to reformulate current active ingredients specifically for use in UAS and regulatory agencies to quickly approve them. Reducing the mass and bulk of insecticides with a concomitant increase in the active ingredient concentration will enable UAS to apply them at lower rates and for longer durations. This coupled to advancements that increase battery duration will make UAS a far better alternative to time-consuming ground-based or costly manned aircraft applications. There is great profit to be realized by pesticide manufacturers if UAS are more broadly employed for controlling pests to protect public health and agriculture.

The development of effective and lightweight mosquito traps that are deployed using UAS would increase the capacity of MCP globally to establish a dense but low-cost abundance monitoring program that would better inform control efforts. The Microsoft Premonition Smart Trap started a revolution in designing automated traps that identify the mosquitoes that are captured (Linn 2016). This effort has been followed by others that use simple cell phone cameras or microphones to identify mosquitoes and automated traps that carried by UAS (Mukundarajan et al. 2017, Minakshi et al. 2018, Ye et al. 2020). UAS and associated trap modules could be readily deployed to remote locations, remain in place to provide real-time mosquito and public health risk data, and autonomously fly back to a main station as needed. When these UAS work in conjunction with swarm technology and charging stations, a world of possibilities will unfold. Not only will this translate to additional horizontal acreage that can be covered by the UAS, but it can also increase surveillance vertically in forest canopies and even high-rise living buildings that are becoming more prevalent globally. Improving automated traps for use with UAS should remain a high priority research objective in the coming years.

Environmental and health concerns can evoke responses from the public and legislators when pesticides are used for mosquito control. UAS have great potential for increased precision in pesticide applications at lower altitudes, thereby reducing pesticide drift and impact on adjacent habitats. UAS are not yet widely employed enough for mosquito control to gauge public perspective on their actual use. Thus, MCP should engage in public outreach well in advance of pesticide applications by UAS. As the monitoring and control approaches currently used by MCP are transitioned from traditional vehicles to UAS, it may become commonplace to incorporate novel technologies into an established UAS-based MCP. For example, rapid and safe delivery of adult non-biting male mosquitoes for use in classic SIT or other control techniques like *Wolbachia* or genetically sterilized mosquitoes (Harris et al. 2012, Crawford et al. 2020), should be investigated as the feasibility of deploying these methods will likely increase. Emphasis should be placed upon developing efficient live-mosquito delivery modules, determining density of organisms that can be safely packed in a delivery module, optimal UAS flying speeds, temperature, altitude, and time and location of male mosquito releases. Public outreach and community engagement should be prioritized, as most of these novel methods can be controversial, and public buy-in is imperative.

UAS technologies for mosquito control are being developed in the public and private sector. Increased collaboration, data sharing, and networking would minimize duplicated efforts. Notably, many are designing and 3D-printing their own components for use with UAS, but much of this information remains in-house and not disseminated broadly. To streamline communication among UAS users in MCP, digital designs for 3D printed objects can be shared freely via the MakerBot Thingiverse website (MakerBot, LLC, New York City, NY) under "Mosquito Control'. Designs can be modified or constructed de novo using Autodesk Tinkercad or Fusion 360 (Autodesk, Mill Valley, CA) software. Tinkercad is a free, easy-to-use program for 3D design that is used globally by students, hobbyists, professionals, and designers. Fusion 360 is free for noncommercial use and comprehensive. We encourage the profession to readily utilize these designs, make their own, and upload the finished designs onto the above website so that others may benefit as well. Only through the sharing and dissemination of information will these accomplishments be truly realized and the profession progress forward.

We encourage interdisciplinary collaborations between government agencies, public health stewards, private industry, and most importantly academia. Most professionals in mosquito and vector control are environmental scientists, biologists, entomologists, and public health specialists. In contrast, there is a dearth of engineers, computer and data scientists, and fabricators. Most of the work that we have accomplished so far has been through sheer necessity. To best exploit the full capabilities UAS and associated platforms for mosquito control, a multidisciplinary approach will be needed. The rewards of these associations have already been realized, as evidenced by the many UAS advances described herein. Individuals with a creative and gritty mindset should be encouraged to transform UAS technologies, spread their own wings, and improve quality of life and public health.

Considerations and Restrictions

It should be noted that we still have a long way to go and there are also certain considerations and limitations that should be considered when adopting this technology. Regulatory requirements stipulated by the FAA have leaned toward limiting rather than promoting broad use of UAS for mosquito control. Such an approach by a federal agency was appropriate when larger UAS became more widely available. As demonstrated safe use of UAS skyrocket, the FAA should and is revising some regulations while imposing others that are primarily aimed at monitoring UAS in the national airspace. Now, owners of recreational UAS weighing over 0.25 kg must be registered with the FAA, fly less than 120 m above ground level, visually keep the UAS within a direct line of sight of the pilot, and follow some additional safety and maintenance rules (FAA 2021). By September 2023, all UAS must use an active remote ID broadcast module that transmits the UAS location and identification to other parties (FAA 2020). For commercial purposes, the same rules apply, in addition to many others, including the requirement for UAS pilots to pass a knowledge test and become certified directly through the FAA (FAA 2021). For pesticide applications, UAS pilots must be licensed and often need supplementary waivers and exemptions (Petty 2018). The cost of training and licensure ranges from nominal if pilots elect to study using free or inexpensive training guides to several hundred dollars for online or in-person courses. Exemptions have not been difficult to obtain at the local level by MCP; however, the ever-changing regulations and lack of consistency can make this process difficult to standardize across the nation. The requirement for the UAS pilot to maintain a visual line of sight hampers the possibility of remotely piloted pesticide application from a central location. If the future lies in being able to remotely pilot a UAS from the safety of a main office, these regulations must be revised. MCP operating UAS near or in controlled airspaces (B, C, D, E airspace) must be reassessed; they do not pose the same threats as larger manned aircraft, as they are much smaller in size, are piloted at low altitudes (usually > 33 m above the ground) and operate within a defined geofenced area. Thus, they should be treated differently to allow for applications particularly in areas close to controlled airspaces that cannot be accessed by larger craft.

Privacy concerns are also a major topic worthy of discussion, particularly in peridomestic habitats. Currently, rural use of UAS has not evoked privacy concerns. These habitats are often remote or inaccessible to the public. Regulations and policies must be adhered to strictly by MCP, and vigilance to such is strongly encouraged when operating UAS where population densities are high (e.g., urbanized areas). We strongly agree with the recommendations by Case et al. (2020) that "if vector control agencies decide to use UAVs in populated areas to monitor mosquito habitat, they produce a document of best practices (including, e.g., blurring personal information like license plates and faces), a rigorous privacy policy, and hold community meetings to inform and engage local citizens about these efforts prior to data collection." A voluntary best practice for UAS privacy, transparency, and accountability has been published by the National Telecommunication and Information Administration as a guide and is available for all entities to use (NTIA 2016). We also urge MCP to completely engage their constituents and remain fully transparent with all aspects of their operations. Similar to community engagement and public education efforts for mosquito control, UAS should also be openly discussed and citizens should be provided an avenue to share their concerns and have an open dialogue about the strengths and weaknesses of this new technology.

The high mobility of UAS, both in rural and urban habitats, makes them a useful tool for mosquito monitoring and control operations. Although these systems are still in the infancy of development, the potential for growth and broad adoption is great within MCP. We understand that in addition to the many benefits that these systems afford us, there are many weaknesses that must be addressed. But in the end, the value of UAS likely outweighs the negative. These systems may soon become the norm and adopting technology will lead to greater benefits for the protection of public health and quality of life across the globe.

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