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PREPARATIONS AND ACTIVITIES NECESSARY FOR AERIAL MOSQUITO CONTROL AFTER HURRICANES

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ABSTRACT. Vector Disease Control International (VDCI) has a long history of aiding mosquito control efforts necessary for recovery after natural disasters like hurricanes and major floods. As waters associated with these events begin to recede, both nuisance and vector mosquito species surge in abundance and consequently play an increased role in public health. When these situations arise, state and county agencies implement emergency response plans and many rely on Federal Emergency Management Agency or private contractors for assistance in reducing mosquito populations that can alter arbovirus transmission cycles, cause intolerable stress, hamper reconstruction efforts, and disrupt normal community functions. Vector Disease Control International owns the largest fleet of fixed-wing aircraft dedicated specifically to mosquito control and has worked every major storm event since Hurricane Bonnie in 1998. This article describes the logistics and operations required for implementing VDCI's emergency management plan, including the relocation of equipment, adult mosquito surveillance, delivery of pesticides, assessment of efficacy, and filing of low-level waivers and congested-area plans with the Federal Aviation Administration.

KEY WORDS Aerial, adulticide, emergency, flood, hurricane, response

INTRODUCTION

In the wake of natural disasters like hurricanes or major floods, it is important that communities have emergency response plans in place (ASTHO 2018). These plans begin with an understanding of what can happen in worst-case scenarios and specify procedures for managing unexpected situations. In addition to immediate challenges such as structural damage, downed power lines, sanitation, displaced populations, and lack of clean drinking water, mosquitoes become a problem as eggs laid on the soil by floodwater species hatch and emerge in massive quantities as biting adults (Simpson 2006, Watson et al. 2007). While nuisance species most common after natural disasters are unlikely to spread pathogens that make people sick, the most effective mosquito control programs suppress both nuisance and pathogen-bearing mosquitoes to protect public health (Palmisano et al. 2005, Del Rosario et al. 2014). Many of the mosquito species associated with hurricane relief are aggressive biters and slow recovery efforts by disrupting first-responder services (fire, police, ambulance, etc.) and causing intolerable stress in resident human populations (CDC 1996, Brown 1997).

Following a large hurricane or storm event there are several factors that increase the risk of vector-borne disease transmission, including higher populations of susceptible hosts, overwhelmed public health services, and disruptions in routine mosquito control operations (Watson et al. 2007, Harris et al. 2014). Emergency situations also strain equipment and staffing resources for local programs. The private sector's role in recovery and rebuilding after hurricanes is vital (Eosco and Hooke 2006), and for many state or county agencies emergency mosquito control simply means having a contingency contract in place. For a private contractor helping to enact that contingency plan, it means setting up an office in an unfamiliar location and relocating the appropriate personnel, fleet, and technology to the area of concern while maintaining services for regular customers. Despite myriad challenges and limited resources in areas of distress, VDCI makes the impossible seem routine and seamlessly activates our emergency response action plan, which is divided into 3 phases:

1) Premission: finding a place to work, relocating people and equipment, mapping, preflight surveillance, product acquisition, and public relations;
2) Mission: mosquito surveillance and identification, adult mosquito control with aerial ultra-low volume (ULV) application equipment;
3) Postmission: assessing efficacy, final mapping, and reports to customer.

PHASE 1: PREMISSION PREPAREDNESS

The Atlantic hurricane season runs from June 1 to November 30, and during that time VDCI staff remain vigilant of storms likely to make landfall. Preparing and having emergency plans in place are critical for any disaster response plan. Over the years, we have refined our preparedness plans and can group them into several priorities: response crew readiness, housing, surveillance data necessary for emergency declarations, geographic information systems (GIS) data preparations, aircraft readiness, airport/staging area locations, fuel, Federal Aviation Administration (FAA) congested-area plans, and product availability.

A standard hurricane deployment team consists of at least 20 individuals pulled from existing operations around the country: 1 on-site manager, 3 2-person surveillance teams, 2 entomologists, 6 pilots, 2 mixing loading crews, 1 certified mechanic, 1 GIS specialist, and a safety coordinator. Securing housing for a team of this size is challenging when many existing structures are badly damaged. With displaced populations crowded into evacuation centers and hotels in nearby towns, our crews are left scrambling for housing. After Hurricane Katrina (Louisiana) we could not secure housing. Consequently, our crews took an unusual step to get the job done and used their personal recreational vehicles (RVs), sleeping in shifts with surveillance crews and mechanics working the day shift and pilots and loaders working all night. After Hurricane Harvey (Texas), housing was difficult to find, even in RV parks. In the end, our surveillance crews were "centrally" located and drove an average of 342 mi (550 km) a day to set traps for 13 counties. Meanwhile, the pilots and loading crews had to initially sleep across state lines and commute to the loading airport each day prior to the mission.

While adult mosquitoes are unlikely to survive the high winds associated with hurricanes, 2–3 weeks after the storm makes landfall mosquito abundance will peak and requests for assistance begin (Breidenbaugh et al. 2008). During this time local officials are typically involved with first-response and recovery efforts. As mosquitoes emerge in mass quantities, they hamper these response and recovery teams. At that point the Federal Emergency Management Agency (FEMA) is called upon to provide reimbursement for mosquito abatement measures at the written request of the state, territorial, tribal, or local public health officials and after consultation with the Centers for Disease Control and Prevention (CDC) (FEMA 2018). Federal Emergency Management Agency may require documentation of increased virus-transmitting mosquitoes in the disaster area, a significant number of mosquitoes in the area due to flooding or standing water, the potential for disease transmission based on the detection of arboviral diseases in sentinel organisms (poultry, wild birds, mosquito pools) or humans in the impacted area prior to the storm event, or a determination that a significant increase or change in the mosquito population poses a threat to emergency workers who are required to work out-of-doors, thereby significantly hampering response and recovery efforts (FEMA 2018). Once requests are made, state and local jurisdictional contingency plans for mosquito control are activated.

As required by FEMA, and because responsible mosquito control professionals employ control measures based on spatiotemporal tracking of mosquito populations, surveillance of the local mosquito population is critical (Lambrechts et al. 2009, CDC 2013). The 1st coordinated task for our staff and local agencies is often to determine the need for mosquito surveillance data. Historical data for an area are not always available but wide-area surveillance using CO_2-baited light traps allows us to identify the size and scope of the situation and adjust treatment strategies as necessary (Ginsberg 2001). For this reason, our surveillance teams are typically the first to arrive and last to leave.

On-board GIS are paramount to our success in navigating unfamiliar terrain for both surveillance and aerial or ground interventions. The initial task of the GIS specialist is to begin coordinating potential counties of operation with federal and state agencies. Base map layers are acquired, potential spray blocks are formulated, potential airports for our operations are pinpointed, and FAA maps are drawn. If it is determined that our staff will need to conduct surveillance rather than local agencies, potential trap sites are located based on proximity to water bodies, land use/cover, human population, and soil types.

Aerial applications are generally preferred after natural disaster flooding events because trucks have limited access due to road closures, downed trees, and compromised infrastructure (CDC 1993, Simpson 2006, Breidenbaugh et al. 2008). Furthermore, given equal manpower, a single aircraft can treat 40,000–45,000 acres (16,187–18,218 ha) per night and trucks typically cover only 80–90 road miles (approximately 3,091 acres) in a single evening. While limited, truck applications do play an integral part in disaster response. Local mosquito abatement districts often supplement the larger scale aerial applications with truck applications. Vector Disease Control International has also been requested to conduct truck-based ULV applications in multiple counties following Hurricane Irma (Florida) and Hurricane Florence (North Carolina).

Finally, after several intense days of planning and coordination our teams convene in the area of operation from across the USA.

PHASE 2: ADULT MOSQUITO CONTROL VIA AERIAL ULV APPLICATIONS

Arriving at the area of operation, there are typically 2 priorities: meet with local airport operations staff and set up a mobile laboratory/office. At the airport our chief pilot will verify a secure location for pesticide storage, confirm 18-wheeler access, locate a place for loading and refueling the planes, and secure a means for unloading pesticide drums. While delivery and storage of product should be easy, freight vehicles are often stretched thin and requiring specialized equipment can delay delivery by days or weeks. While operations are beginning at the airport, surveillance teams are setting up space to prepare traps, identify mosquitoes, and store specimens. Dry ice is often a precious commodity and becomes challenging to find. In some cases a single individual's sole responsibility is to drive several hours, each way, every day to purchase enough dry ice for the trapping teams.

Pilots begin preflying the intended spray zones almost immediately. Under normal circumstances, aerial mosquito control is a dangerous profession. After hurricanes, the danger increases. Power outages mean that towers and other tall obstructions may not be lit. We spend considerable time and energy ensuring the FAA tower database is loaded into each aircraft's guidance system and then each tower's location and height is visually verified during the daily preflight missions. In addition to the preflights, all planes undergo an operational checklist of the entire spray system, including rotary atomizers for droplet spectrum control, on-board drift management software, and real-time weather monitoring. Predetermined models for each pesticide used are loaded into the system and spray blocks verified.

Vector Disease Control International's aerial fleet consists of small, twin-engine aircraft, including 5 Piper Aztecs (PA23/250), 2 Piper Chieftains (PA 31/350), and 1 Cessna 402C. When looking for a facility to work out of, small aircraft are advantageous because we can use short runways (4,500–6,000 ft [1,370–1,830 m]) and often find sites that are adjacent to, or directly in, our spray zones. All aircraft are certified by the FAA and comply with requirements of Federal Aviation Regulation Part 137, Agricultural Operation. Each plane is equipped with a Wingman™ GX spray management system (ADAPCO, An Azelis Company, Sanford, FL) in combination with an Aircraft-Integrated Meteorological Measurement System-20 (Aventech Research, Inc., Barrie, Ontario, Canada). The spray systems are highlighted by 2 Micronair AU-4000 rotary atomizer nozzles (Micron Sprayers Ltd., Bromyard, United Kingdom); an automatic flow control system for aerial applications, Auto Cal II (Auto Control, Inc., Houma, LA); and a 90- to 100-gal (340.7- to 681.4-liter) chemical tank with an integrated 5-gal (18.9-liter) flush tank and 5-gal (18.9-liter) rinse tank.

The logistics for treating large areas under a disaster declaration, and simultaneously working for as many as 10–15 counties, requires extensive coordination, planning, and mobility as information changes daily from the surveillance teams, aerial application teams, and local, state, and federal agencies and all operations are in a state of continual flux. Operational parameters can change not just daily, but hourly. Aerial mosquito control applications normally require local governmental approval and that is often still the case in disaster declarations. Constant communication with state and county officials is essential, as spray zones can change hours before an application. Each change may require new spray blocks to be delineated by the GIS staff. Then the pilot must load the information into the aircraft flight system and ensure the area has been preflown for obstructions. The surveillance teams may need to perform last-minute landing rate counts to get preapplication data. Meanwhile, the product is not always delivered to the proper loading site or airport and needs to be located and all possible methods used to get it to the airport in time for the night's applications. Crews are in the public eye, with media requesting interviews and footage of the aircraft. Meanwhile, the various state regulatory agencies need to conduct inspections of the operations to confirm compliance with state laws.

To illustrate the dynamic nature of these applications, we can look at the instance of Jasper County, TX, after Hurricane Harvey. Jasper County was one of the first counties designated to be treated by VDCI. Texas Department of State Health Services (DSHS) notified us of potential areas to begin surveillance and treatments on September 10, 2017. On September 13, we had crews in Jasper (and Newton) County setting preapplication CDC light traps and planned to treat 176,750 acres (71,528 ha) with Dibrom® Concentrate (AMVAC Chemical Corporation, Newport Beach, CA) at a rate of 0.7 oz/acre (51 ml/ha) on September 15. Thirty-three drums of product were ordered and shipped to Beaumont, TX, where our flight crews were based at that time. The following morning, September 14, as the surveillance teams were picking up the traps, the county commissioners decided, under pressure from beekeepers, to pull out of the application. The traps were sorted and identified. On September 15, DSHS informed us that the County was reconsidering their decision. On September 16, the County officially requested an application again, but decided to reduce the block size to 125,776 acres (5,179 ha) in the southern portion of the county. Spray blocks were drawn up and we adjusted the product order as only 23 drums were now needed. Traps for Jasper County were reset on the night of September 17 and our base of operations was now on the verge of moving to Huntsville, TX, as we were assigned several counties (San Jacinto and Polk) north of Houston. We bumped Jasper down the list as it was suggested that the county commissioners were continuing to deliberate. A couple of days later, September 20, DSHS informed us that the block size was increased to 534,777 acres (216,416 ha), nearly covering the entire county. For this application we needed 97.5 drums of Dibrom Concentrate and began making plans to relocate our aerial operations to Jasper. On September 23, 2017, we began aerial applications in Jasper County. In the span of 10 days, the block size was changed 3 times, 3 orders of product had to be moved, and we worked from 3 different airports. We finished the Jasper block on September 26, 2017, with postapplication surveillance concluding on September 28.

While the Jasper County example is extreme, few applications occur exactly as planned or initially requested. There is a need for all parties involved, from the state and local agency staff, to the aerial and surveillance teams, to the product manufacturer, to the local population helping us at the airports and hotels to be flexible and understanding of the frantic situation playing out in real time. Despite continual changes and stressful situations, mosquito control does occur and surveillance data are used to determine the need, timing, location, and efficacy of each application.

Mosquito populations can be diverse in the wake of a hurricane or a large-scale flood event (Barrera et al. 2019). For the hurricane response deployments in 2017 and 2018, VDCI conducted landing rate counts (Schmidt 1989) and used standard CDC miniature light traps (Model 512; John W. Hock Company, Gainesville, FL) baited with approximately 1.4 kg (3 lb) of dry ice, suspended in a 1-gallon Coleman drink cooler, powered with a rechargeable, sealed, gelled-electrolyte 6-V battery. Traps were set within approved spray zones and their locations mapped using Global Positioning System coordinates. The number of traps per county ranged from 4 to 10, based on the size and number of spray blocks in each county. Traps were set in locations with vegetative cover, protected from the wind, and away from direct sunlight or artificial light sources. The same trap locations were sampled before and after each spray mission. The number of days between prespray and postspray surveillance was determined by the number of nights it took to successfully complete a county's application mission.

All traps were set in the afternoon hours prior to sunset, collected the following morning, and returned to our surveillance base of operations in a cooler containing dry ice. Enumerated and speciated mosquito totals were recorded and in the event of a large trap collection (>1,000 mosquitoes), the total trap count and species composition were estimated. For this, both the entire trap collection and a representative subsample were removed and weighed. To estimate the trap total count (TC), the subsample total count (SC) was divided by the subsample weight (SW) and then multiplied by the total weight (TW):

$$\mathrm{TC} = (\mathrm{SC}/\mathrm{SW}) \times \mathrm{TW}.$$

To estimate the number of specimens of each species in the total count (TSC), the species count in the subsample (SCS) was divided by the SC and multiplied by 100. This calculation provides the percentage of that species in the SC (PSC):

$$\mathrm{PSC} = (\mathrm{SCS}/\mathrm{SC}) \times 100.$$

Finally, the TC is multiplied by the PSC and divided by 100 to yield the TSC:

$$\mathrm{TSC} = (\mathrm{TC} \times \mathrm{PSC})/100.$$

In North Carolina, after Hurricane Florence (2018), we conducted surveillance in 3 counties (Carteret, Johnston, and Wilson). Thirty-two species of mosquito were collected, with 26,896 specimens in 54 trap-nights (pre- and postapplication combined; Table 1). The majority (n = 68.6%) of our North Carolina collections comprised 4 species. *Aedes atlanticus* Dyar and Knab was the most abundant species collected, comprising 23.3% of the total. *Psorophora ferox* (L.) represented 18.9% of collected specimens, while *Aedes vexans* (Meigen) and *Culex salinarius* Coquillett represented 13.7% and 12.7%, respectively.

Table 1. Mosquito diversity and abundance in collections from Carteret, Johnston, and Wilson counties in North Carolina after Hurricane Florence, October 4–15, 2018.

Mosquito species	Total collected	% of total
Aedes albopictus	341	1.3
Ae. atlanticus	6,258	23.3
Ae. canadensis	600	2.2
Ae. cinereus	21	0.1
Ae. dupreei	655	2.4
Ae. fulvus pallens	25	0.1
Ae. hendersoni	3	0.0
Ae. infirmatus	1,108	4.1
Ae. mitchellae	15	0.1
Ae. sollicitans	2	0.0
Ae. taeniorhynchus	370	1.4
Ae. triseriatus	23	0.1
Ae. vexans	3,687	13.7
Anopheles crucians	941	3.5
An. perplexans	6	0.0
An. punctipennis	162	0.6
An. quadrimaculatus	265	1.0
Coquillettidia perturbans	19	0.1
Culex erraticus	133	0.5
Cx. nigripalpus	3	0.0
Cx. pipiens	571	2.1
Cx. quinquefasciatus	5	0.0
Cx. salinarius	3,407	12.7
Culex spp.	52	0.2
Cx. territans	22	0.1
Culiseta melanura	2,448	9.1
Psorophora ciliata	76	0.3
Ps. columbiae	273	1.0
Ps. ferox	5,087	18.9
Ps. horrida	247	0.9
Ps. howardii	20	0.1
Ps. mathesoni	11	0.0
Uranotaenia sapphirina	40	0.1
Total	26,896	100.0

Given the diversity of species collected, the window of application can vary considerably. Typical aerial applications are intended to control 1, or possibly 2 species. As evidenced by the collections in North Carolina, our goal is to target multiple species with a wide range of activity patterns. In some instances applications can extend into the early morning hours and still achieve good control, while for other missions, the species composition may limit the application window to within several hours of sunset. When dealing with a large variety of mosquito activity peaks after a large-scale flood event, we have observed that Dibrom at rates of 0.7–1 oz/acre (51–73 ml/ha) can yield significant knockdown of many species, with applications occurring throughout the late evening and early morning hours. In Johnston County, NC, we observed a 99.4% knockdown of *Ae. atlanticus* and a 98.0% knockdown of *Ps. ferox*, with applications occurring between 9:00 p.m. and 2:00 a.m. However, not all species experienced the same level of control. *Culex salinarius* numbers were reduced by only 54.3% and *Ae. vexans* by 51.2%. Overall application efficacy in Johnston County was measured at 88.59%, applying Dibrom Concentrate at 0.7 oz/acre. There are difficulties with drawing hard species-specific conclusions from our trap data because applications to such large areas can take multiple nights to complete. In Johnston County applications occurred over 2 nights (September 6 and 8) with an intervening weather delay. Although the preapplication traps were set on September 5 and the postapplication traps were set on September 9, there were 3 nights between the pre- and postapplication trapping efforts for some trap locations.

It is difficult to say when a typical application night's activities begin, because they never completely end during a hurricane response. Each day begins by addressing any mechanical issues that arose from the night before. From replacing check valves or landing gear and performing 50-h and 100-h inspections, VDCI's mechanics work around the clock to keep the planes flying. By the time the pilots begin preflight surveillance, the mechanics have been working since the early morning, while the loading crews move and replace pesticide drums. As evening approaches, aircraft preflight checks are performed, the latest spray blocks are uploaded and verified, and the pilot's briefing establishes that night's flight patterns. Loading crews normally begin loading planes 1 h before sunset. Immediately after loading, the planes begin their respective missions. Our staff works closely with local airport staff to ensure a fuel truck is on hand at all hours, as planes return for the next load and refueling. The hum of planes, generators, and forklifts continues throughout the night until the last plane is rinsed and parked. Pilots average 4 loads per night, depending on weather, block size, predetermined application window, and even fatigue. In 2017 one of our pilots flew 9 loads in a single evening. Hurricanes Harvey and Irma in 2017 were particularly challenging for our crews. Over a 6-day period (September 19–24, 2017) we worked out of 6 different airports. On a single night we had loading crews, mechanics, pilots, and equipment in 3 separate airports across 2 states.

PHASE 3: POSTMISSION CLEANUP AND ASSESSMENT

When application activities are complete, postapplication traps have been collected and mosquitoes identified, the team can finally rest. At this point equipment is cleaned and arrangements are made for the pickup or removal of empty pesticide drums. As needed, data are verified, final reports are submitted, and application records stored.

There were 2 major hurricane events in 2017 that resulted in federal natural disaster declarations and aerial mosquito control operations. Hurricane Harvey and Hurricane Irma were particularly challenging due to the geographic breadth of counties treated and the need for simultaneous operations in multiple states. In Texas, we operated in 7 counties from 3 airports (Fig. 1A). In Florida, VDCI conducted aerial applications in 16 counties, operating from 7 airports (Fig. 1B). In Louisiana, we treated 2 parishes from a single airport (not shown). In total, 3,680,826 acres (1,489,577 ha) were treated (1,914,912 acres for Hurricane Harvey in Texas and Louisiana) and 1,765,914 acres (714,640 ha) for Hurricane Irma in Florida (Fig. 1C). The maximum acreage treated in a single night was 404,880 acres (163,849 ha) on the night of September 23, 2017, with simultaneous applications in 4 counties (2 in Texas and 2 in Florida). Our 1st application began on September 5 in Louisiana, September 14 in Texas, and September 18 in Florida (Fig. 1C). The final application occurred on September 12 in Louisiana (5 total application-nights), September 26 in Texas (13 total application-nights), and October 3 in Florida (15 total application-nights).

In 2018, there were 2 major hurricanes with federal natural disaster declarations that resulted in aerial mosquito control operations—Hurricane Florence (North Carolina) and Hurricane Michael (Florida). Within North Carolina, we conducted operations in 4 counties, operating from 2 airports (Fig. 2A). In Florida, we treated 4 counties, operating from 1 airport (Fig. 2B). Our total disaster response in 2018 consisted of 1,511,164 acres (611,546 ha) treated: with 919,272 acres (372,016 ha) in North Carolina in response to Hurricane Florence and 591,892 acres (239,530 ha) treated in Florida after Hurricane Michael (Fig. 2C). The maximum treatment in a single night was 285,092 acres (115,372 ha) in Johnston County on the night of October 6, 2018. Our 1st application began on October 2 in North Carolina and October 15 in Florida (Fig. 2C). The final application occurred on October 8 in North Carolina (6 total application-nights) and October 24 in Florida (5 total application-nights).

CONCLUSIONS

Within the weeks following a hurricane or large storm event, there is a multitude of issues that can affect the response and recovery efforts. In addition to the basic concerns of housing, food, and shelter, mosquito abundance can dramatically increase and affect displaced residents' and recovery crew's health. Areas flooded from the tidal surges, heavy rains, and swollen rivers all contribute to a diverse mixture of mosquito species. Prominent nuisance species belonging to the genera *Aedes* and *Psorophora* can dramatically impact humans and live-

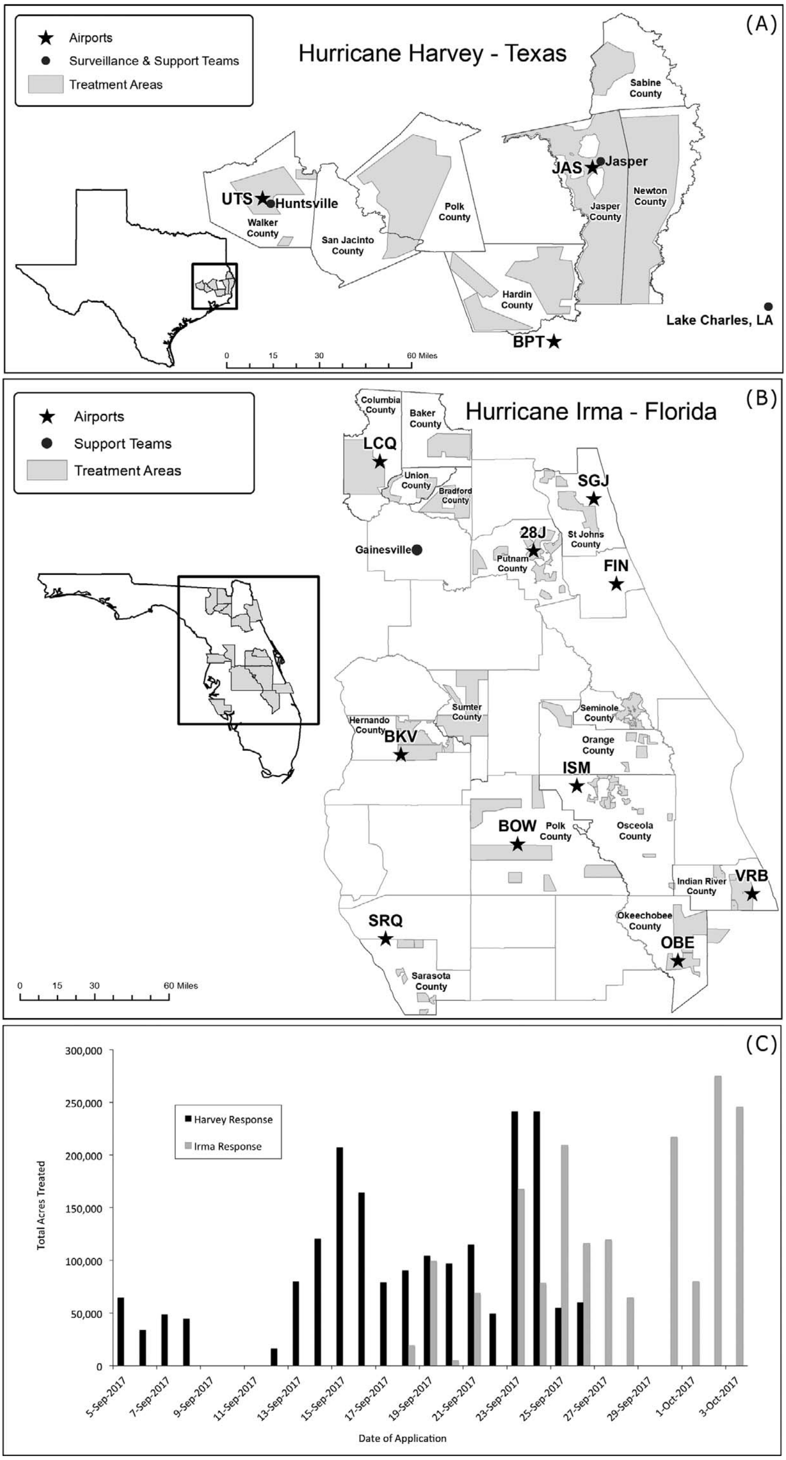

Fig. 1. Hurricane response in 2017—counties where Vector Disease Control International (VDCI) performed aerial applications, delineating airports of operation and surveillance team base locations (A) in Texas after Hurricane Harvey and (B) in Florida after Hurricane Irma, and (C) the total number of acres treated each night.

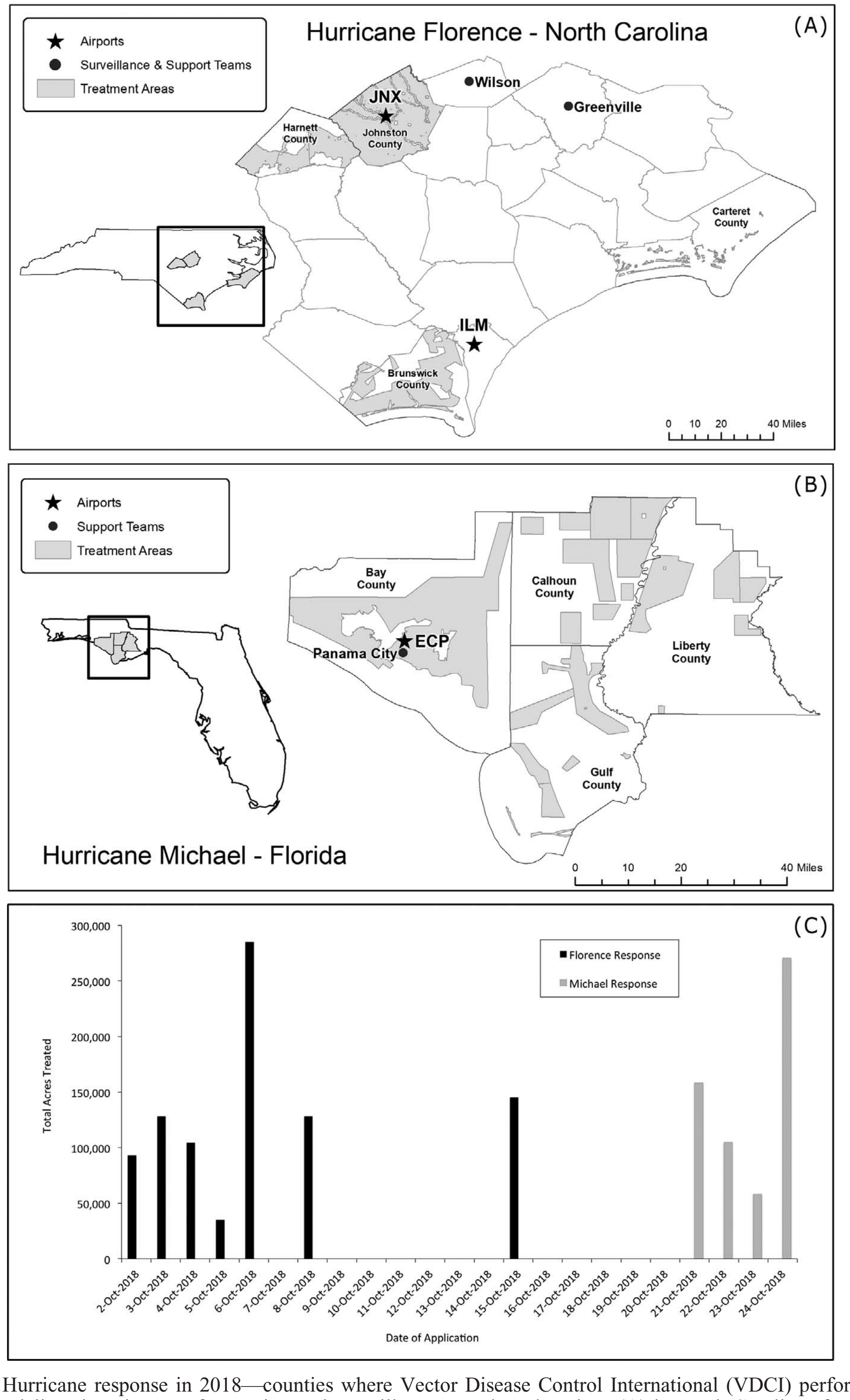

Fig. 2. Hurricane response in 2018—counties where Vector Disease Control International (VDCI) performed aerial applications, delineating airports of operation and surveillance team base locations (A) in North Carolina after Hurricane Florence and (B) in Florida after Hurricane Michael, and (C) the total number acres of treated per night.

stock, whereas mosquitoes of the genera *Aedes* and *Culex* have the ability to transmit pathogens and contribute to a large public health threat. Without intervention, mosquito populations impede recovery and reconstruction activities.

ACKNOWLEDGMENTS

The authors note that although this paper represents VDCI and our colleagues' work during a hurricane mosquito response outbreak, we acknowledge and recognize that our efforts are but a piece of the response. There are numerous federal and state agencies, county and municipal staff, other private contractors along with product manufacturers and distributors, and the staff of numerous mosquito abatement districts all doing their part to lower the mosquito burden in the affected areas.

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