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TEXAS MOSQUITO CONTROL RESPONSE FOLLOWING HURRICANE HARVEY

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ABSTRACT. Hurricane Harvey has been recorded as the wettest cyclone in United States history, resulting in devastating and catastrophic flooding for the Texas Gulf Coast. The nature of the path of the hurricane, with multiple landfalls along the Texas Gulf Coast, resulted in the largest aerial mosquito control effort for one single storm. Two mosquito control contractors and the Air Force Aerial Spray Unit of the US Air Force Reserve were used to aerial treat 6,765,971 acres (3,075,441 ha) in 29 of the 60 disaster-declared counties in Texas. During the response, 101,253 liters of Dibrom® (active ingredient [AI]: naled) and 48,735 liters of Duet™ (AI: 1% prallethrin and 5% sumithrin) were used. In 23/29 counties requesting aerial spraying, mosquito control contractors were used to conduct pre- and postaerial application mosquito surveillance. The remaining 6 counties conducted their own surveillance during the response. A total of 105,153 mosquitoes in 7 genera and 35 species were collected during this response with the major floodwater nuisance mosquito being *Psorophora columbiae*. The most abundant vector mosquito collected was *Culex nigripalpus*. Duet at the 0.8% and 1% application rates resulted in 49% and 69% control of *Ps. columbiae*, respectively. Dibrom application resulted in 95% and 93% control of *Ps. Columbia* and *Cx. nigripalpus* populations, respectively.

KEY WORDS Aerial applications, emergency response, floodwater mosquitoes, hurricane, naled

INTRODUCTION

On August 25, 2017, Hurricane Harvey made landfall along the Texas Gulf Coast as a Category 4 storm (https://www.weather.gov/hgx/hurricaneharvey). Following a path along the Texas Gulf Coast, Hurricane Harvey ultimately made multiple landfalls and meandered inland for days (Fig. 1). This resulted in the wettest cyclone on record and the 2 greatest single-storm rainfall totals in the USA (including Hawaii), with 154 cm recorded at weather stations near Port Arthur and Groves, TX (National Weather Service 2017). The storm's hovering inland resulted in catastrophic, devastating, historical, and life-threatening flash and river flooding over southeast Texas. Additionally, because of the hurricane's making multiple landfalls and dumping varying amounts of rain throughout the Texas Gulf Coast, large emergences of floodwater mosquito populations were reported in the Coastal Bend area of Texas as early as 1 wk after landfall. This rapid development of adult mosquitoes following severe flooding was atypical, as demonstrated by the work of Breidenbaugh and Haagsma (2008) that investigated the relationship between hurricanes, mosquito production, and disease transmission. Following these reports of large mosquito populations hindering recovery efforts in the Coastal Bend area, the Texas State Medical Operations Center created the Vector Control Task Force (VCTF) to organize the mosquito response requested through the State of Texas Assistance Requests (STARs) that were submitted by the Emergency Operations Centers (EOCs) activated in the hurricane-impacted jurisdictions. The VCTF consisted of 8 Texas Department of State Health Services (DSHS) employees, 1 of which was the DSHS medical entomologist, and 2 requested subject matter experts: 1 from the Centers for Disease Control and Prevention (CDC) and 1 from the Air Force Aerial Spray Unit (AFASU) of the US Air Force (USAF). This team came together to organize the largest aerial mosquito control response following a single hurricane with the purpose of alleviating the nuisance mosquito burden to allow for recovery efforts in areas impacted by the hurricane.

Supported through the assistance of the Federal Emergency Management Agency (FEMA), within 3 wk of the Presidential Disaster Declaration for 60 impacted counties, 29 of those were aerially treated by the AFASU and 2 state contractors, Clarke Environmental Mosquito Control, St. Charles, Illinois, and Vector Disease Control International, Little Rock, Arkansas (VDCI). In total, more than 6.7 million acres were treated with 101,253 liters of Dibrom® and 48,735 liters of Duet™. This report provides information on the efficacy of the applications and lessons learned that will guide the Texas VCTF in future operations in emergency situations and provide insight to other public health officials facing similar situations in the future.

MATERIALS AND METHODS

Activating aerial spraying

In Texas, local jurisdictions in emergency situations request resources utilizing the STAR process (Texas Department of State Health Services 2019), adjudicated through the incident command structure. The STAR is prioritized based on the submitting jurisdiction's need determined by DSHS. The first

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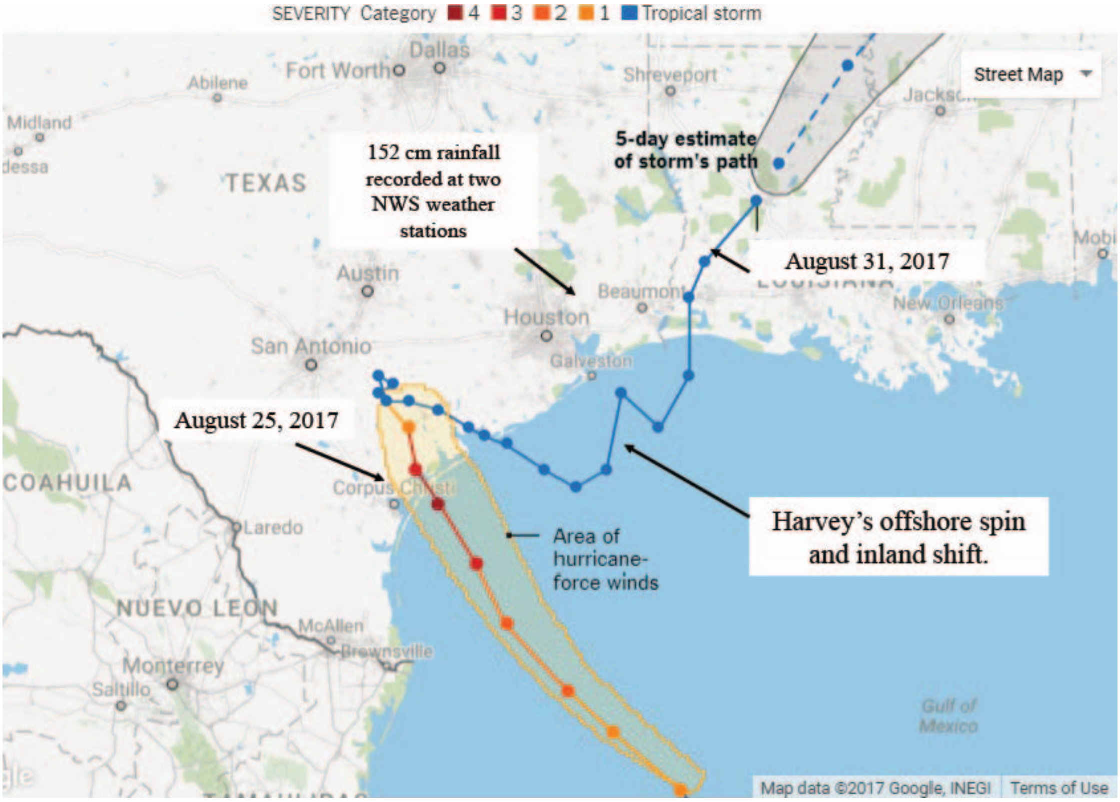

Fig. 1. Hurricane Harvey's path along the Texas Gulf Coast. Over a period of 56 h, Harvey grew from a tropical depression over the Gulf of Mexico into a Category 4 hurricane as it made landfall at Rockport, Texas, on August 25, 2017. From August 25 to August 31, 2017, Harvey stalled over south and southeast Texas, producing catastrophic, devastating, historical, and life-threatening flash and river flooding. The National Weather Service recorded the 2 greatest single-storm rainfall amounts of 152 cm of rain near Port Arthur and Groves, Texas.

STAR was filed with DSHS 4-days post-landfall to initiate aerial sprays for mosquito control on the Coastal Bend and Victoria area, which included 13 counties. Additionally, within 7 days post-landfall, 11 more STARs had been filed for aerial spraying in jurisdictions along the Gulf Coast. Based on this precipitous influx of requests for emergency vector control across a wide area, the Texas DSHS responded with the formation and activation of the VCTF. Due to the expected need, the VCTF worked with the DSHS leadership to request federal support through FEMA. Concurrently, the DSHS activated its preexisting state emergency mosquito control contract with Clarke Environmental Mosquito Control. The President of the United States signed the disaster declaration on September 3, 2017, for the state of Texas and provided a cost-share waiver for 60 counties impacted by the hurricane. An emergency contract was also set up with VDCI to support the large number of counties and total acreage requested for aerial spraying. Table 1 presents the county submitting the STAR for aerial spraying, the contractor providing the aerial spray, the dates of the first round of aerial spraying and any subsequent spray missions, and the acreage covered.

Surveillance activities and spray missions

Because of the varying degree of mosquito control capacity within each disaster-declared county, coupled with the disruption of normal capabilities, very few of the counties could assist in mosquito surveillance. Mosquito abatement resources vary widely in east Texas from counties where this function is nonexistent to robust state-of-the art programs. Nevertheless, all programs were severely affected by the storm, and little to no vector surveillance capacity remained in the disaster-declared region. Fortunately, the programs did an excellent job of rapidly recovering this capability. Furthermore, the state-level staffing was not a practical resource for field deployment; DSHS had 1 medical entomologist, and the VCTF was established to serve a leadership role and therefore did not have the capacity for responding to the large geographical areas to conduct mosquito surveillance, despite an interest in doing so. In 23/29 counties

Table 1. The 69 aerial spray missions by county and contractor with the number of acres treated per aerial application.

County	Contractor	Mission start date (respray start date)	Nights sprayed (nights resprayed)	Acres treated (acres resprayed) [total treated]
Aransas	Clarke	September 7, 2017 (September 14, 2017, September 22, 2017)	1 (2, 2) (total)	38,130 (10,692, 20,228) [69,050]
Bee	Clarke	September 7, 2017 (September 15, 2017)	1 (1) (total)	40,562 (5,699) [46,261]
Nueces	Clarke	September 7, 2017 (September 14, 2017)	3 (2) (total)	375,062 (47,750) [422,812]
Refugio	Clarke	September 7, 2017 (September 13, 2017)	1 (1) (total)	16,039 (3,859) [19,898]
San Patricio	Clarke	September 7, 2017 (September 14, 2017)	1 (2) (total)	121,284 (64,096) [185,380]
Calhoun	Clarke	September 7, 2017 (September 14, 2017, September 20, 2017)	1 (1, 1)	217,588 (72,683, 72,275) [362,546]
Jackson	Clarke	September 10, 2017 (September 15, 2017, September 21, 2017)	1 (1, 2) (total)	164,125 (85,927, 101,602) [351,654]
Dewitt	Clarke	September 10, 2017	1	231,647
Kleberg	Clarke	September 13, 2017	1	60,425
Jim Wells	Clarke	September 13, 2017	1	60,502
Kennedy	Clarke	September 13, 2017	1	32,700
Jackson	Clarke	September 13, 2017	1	153,051
Lavaca	Clarke	September 11, 2017	1	22,435
Wharton	Clarke	September 19, 2017	1	165,194
Waller	Clarke	September 17, 2017	2	274,672
Chambers	Federal	September 12, 2017	4	238,869
Brazoria	Federal	September 14, 2017	4	540,932
Harris	Federal	September 14, 2017	7	574,883
Liberty	Federal	September 14, 2017	1	505,818
Montgomery	Federal	September 15, 2017	3	412,865
Orange	Federal	September 9, 2017	3	152,689
Jefferson	Federal	September 9, 2017	5	208,700
Galveston	Federal	September 21, 2017	1	66,315
Newton	VDCI[1]	September 23, 2017	3	267,429
Polk	VDCI	September 18, 2017	4	176,914
San Jacinto	VDCI	September 18, 2017	4	176,913
Hardin	VDCI	September 15, 2017	3	258,743
Walker	VDCI	September 17, 2017	2	123,245
Sabine	VDCI	September 22, 2017	2	82,286
Jasper	VDCI	September 23, 2017	4	521,143

[1] VDCI, Vector Disease Control International.

requesting aerial spraying, mosquito control contractors were used to conduct pre- and postaerial application mosquito surveillance. Brazoria, Harris, Galveston, Chambers, Jefferson, and Montgomery counties conducted their own surveillance during the response and coordinated with the VCTF.

Once the STAR was submitted and approved, the VCTF geographic information specialists worked with the STAR submitter, usually the EOC Incident Commander, to develop the spray blocks. The spray blocks were centered around areas in the county where responders were conducting recovery efforts and large population centers were located (Watson et al. 2007). These spray blocks were then overlaid onto maps created using ArcGIS (Environmental Systems Research Institute, Redland, CA), which included shape files provided by US Fish and Wildlife Services and US Parks and Recreation Services to avoid impacting endangered species or sensitive lands (Fig. 2a). The maps were approved by the VCTF and the submitting EOC and provided to FEMA for dissemination to other federal and state partners for input and concurrence on the aerial applications. These maps were then provided to the contractors and Air Force to upload in their flight systems and to select mosquito surveillance sites that fell within the spray blocks.

In the 23 counties in which mosquito surveillance was conducted by the contractors, 24–72 h before treatment and 24 h after treatment were used as collection times. In each county, at least 3 mosquito trap sites were selected that fell within the spray blocks (range 3–8) (Fig. 2b). In the counties providing their own mosquito surveillance, all but Montgomery relied on landing rate counts (LRCs) the day of and the next morning after the aerial

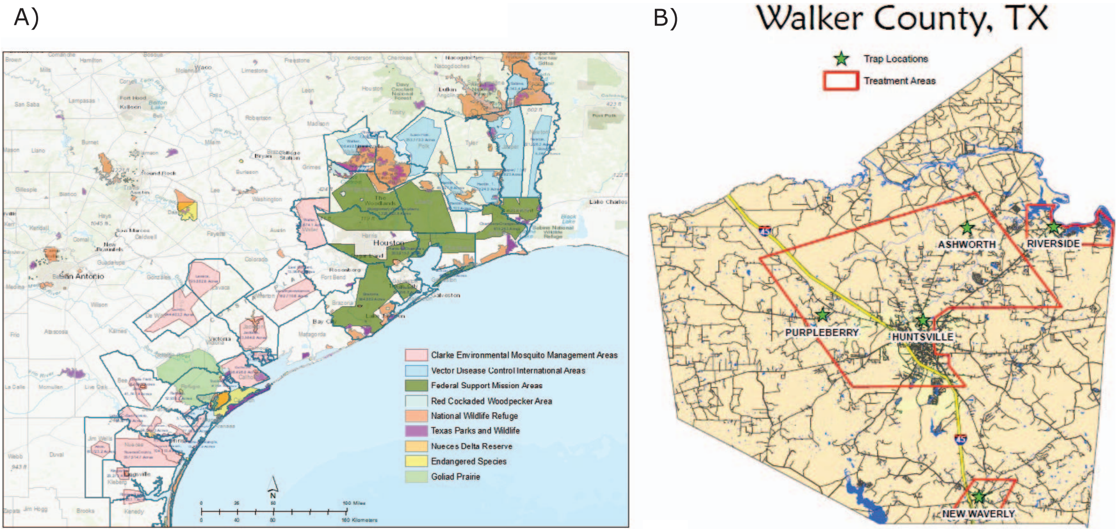

Fig. 2. (A) Map identifying areas to avoid during aerial treatment for mosquitoes such as sensitive lands or endangered species habitat. (B) Example of how mosquito surveillance was conducted within the treatment area. The treatment area in Walker County, Texas, was developed in collaboration with their ECO and the VCTF. The state contractor, VDCI, surveilled and conducted the aerial applications in the treatment area.

application. The Woodlands Township (Montgomery County) and the contractors used CDC light traps baited with dry ice to conduct the mosquito surveillance. The number of traps varied by county due to the time it took to travel to and set up the sites within the county. Trap location, LRC location, LRC numbers, and data on mosquito species were provided to the VCTF. The percentage of control at each trap site was calculated by dividing postspray totals by prespray totals, subtracting from 1.0, and converting into a percentage as follows: % control at site $= 1 -$ (postspray/prespray) $\times$ 100 (Simpson 2006).

Aerial spray missions were conducted between sunset and sunrise using night vision goggles to avoid nontarget impacts and comply with the Texas Department of Agriculture (TDA) regulations. All applications were conducted with a TDA-certified pesticide applicator onboard and used Global Positioning System navigation for proper swath width separation and spray block identification. Clarke used Beechcraft King Airs operated with the Micronair AU-4000 rotary atomizer nozzles (Micron Sprayers Ltd., Bromyard Industrial Estate, Bromyard, Herefordshire, United Kingdom) and applied the treatments at 91 m (300 ft) with a swath width ranging from 300 to 500 m (1000–1500 ft). The VDCI used three Piper Aztecs (PA 23/250) and two Piper Chieftains (PA 31/350) operated with 2 Micronair AU-4000 rotary atomizer nozzles and applied the treatments at 91 m (300 feet) with a swath width ranging from 300 to 500 m (1000–1500 ft). Clarke applied Duet (active ingredient [AI]: 1% prallethrin and 5% sumithrin) at 0.8 ounce/acre and 1.0 ounce/acre and Dibrom (AI: naled at 0.7 ounce/acre). The VDCI applied Dibrom at 0.7 ounce/acre. The AFASU flew 3 C-130H aircraft with 1 additional plane as a spare and applied Dibrom at 0.7 ounce/acre. The C-130 aircraft used 8003 flat-fan nozzles (TeeJet), flew at 370 km/h (230 mph), 91 m (300 ft) above the ground level with a 762 m (2,500 ft) swath width. These spray parameters are typical AFASU operational methods for mosquito control over large areas and at night (Burkett et al. 1996, Breidenbaugh et al. 2000, Breidenbaugh et al. 2008). The total acreage completed by each applicator by product is shown in Table 2.

RESULTS

A total of 29 counties requested aerial spraying, resulting in 6,765,971 acres (3,075,441ha) sprayed (Fig. 3). A total of 105,153 mosquitoes belonging to 7 genera and 35 species were collected during this response: *Aedes aegypti* (L.), *Ae. albopictus* (Skuse), *Ae. atlanticus* Dyar and Knab, *Ae. bimaculatus* Coquillett, *Ae. dupreei* (Coquillet), *Ae. fulves pallens* Dyar and Kanb, *Ae. infirmatus* Dyar and Knab, *Ae. sollicitans* (Walker), *Ae. taenioryhnchus* (Wiedemann), *Ae. thelcter* Dyar, *Ae. triseriatus* (Say), *Ae. vexans* (Meigen), *Anopheles crucians* Weidemann, *An. pseudopunctipennis* Theobald, *An. quadrimaculatus* Say, *Culex coronator* Dyar and Knab, *Cx. erraticus* (Dyar and Knab), *Cx. interrogator* Dyar and Knab, *Cx. nigripalpus* (Theobald), *Cx. quinquefasciatus* Say, *Cx. restuans* (Theobald), *Cx. salinarius Coquillett*, *Cx. tarsalis* (Coquillett), *Cx. territans* Walker, *Coquillettidia perturbans* (Walker), *Culiseta inornata* (Williston), *Mansonia titillans* (Walker), *Psorophora ciliate* (Fabricius), *Ps. columbiae* (Dyar

Table 2. The total acreage completed and liters of product used by contractor.[1]

Contractor	Product and rate (ounce/acre)	Acres	Liters (US gallons)
VDCI	Dibrom 0.7	1,606,673.0	32,009 (8,456)
Clarke	Duet 0.8	1,339,654.7	31,694 (8,372)
Clarke	Duet 1.0	474,729.5	14,041 (3,709)
Clarke	Dibrom 0.7	643,842.3	13,328 (3,521)
DSHS contractor totals		4,064,899.5	91,072 (24,058)
Federal mission (AFASU)	Dibrom 0.7	2,701,071.0	55,916 (14,771)
Aerial spraying totals		6,765,970.5	146,988 (38,829)

[1] AFASU, Air Force Aerial Spray Unit; DSHS, [Texas] Department of State Health Services; VDCI, Vector Disease Control International.

and Kanb), *Ps. cyanescens* Coquillett, *Ps. ferox* (L.), *Ps. horrida* Dyar and Knab, *Ps. howardii* Coquillett, *Ps. mathesoni* Belkin and Heinemann, and *Ps. signipennis* (Coquillett). The percent control by county is shown in Table 3.

The major floodwater mosquito collected was *Ps. columbiae* (22,741/105,153; collected in 21/25 counties trapped). The most mosquitoes collected in one CDC light trap was 13,440 in Waller County, of which 87% (11,712) were *Ps. columbiae*. An important nuisance mosquito, *Ae. Taeniorhynchus*, was frequently collected in the Coastal Bend area (20,810/105,153; collected in 12/24 counties trapped).

The most abundant vector mosquito collected was *Cx. nigripalpus* (10,532/105,153; collected in 18/25 counties trapped). *Culex quinquefasciatus*, Texas's most important West Nile virus vector, was collected in 21/25 counties trapped but represented only about 3% of the total number of mosquitoes sampled (3224/105,153).

The applications of Duet at 0.8 ounce/acre resulted in 17% control and 45% control at 1.0 ounce/acre. Dibrom application resulted in 92% control in mosquito populations. Looking specifically at *Ps. columbiae* and *Cx. nigripalpus*, Dibrom resulted in 95% and 93% control, respectively. Duet at the 0.8%

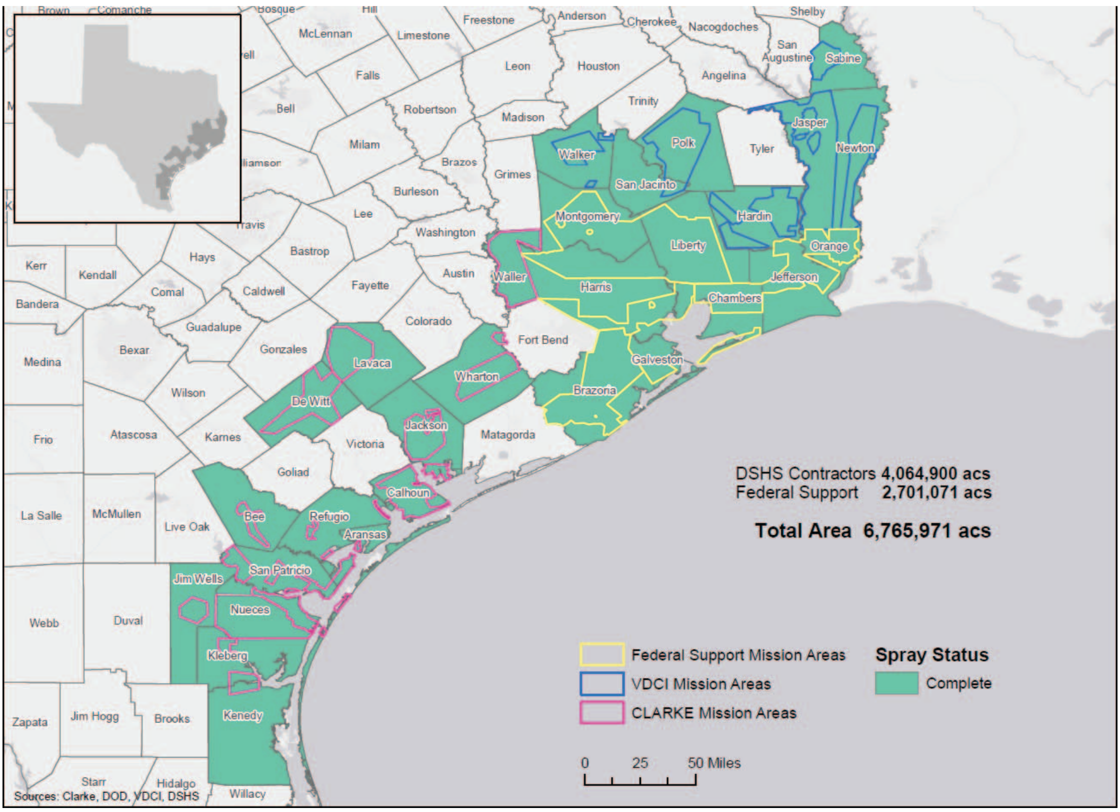

Fig. 3. The map identifies the spray blocks, the contractors responsible, and the counties aerially sprayed following Hurricane Harvey in Texas, 2017.

Table 3. The percent control of mosquito populations following the aerial applications, comparing prespray and postspray mosquitoes collected in CDC[1] dry ice–baited light traps, by county.

County	Chemical	Application rate (ounce/acre)	Prespray trap numbers	Postspray trap numbers	% control
Aransas	Duet	0.8	4,096	2,302	43.8
Bee	Duet	0.8	233	263	−11
Calhoun	Duet	0.8	1,552	3,376	−117
Dewitt	Duet	0.8	510	266	47.8
Nueces	Duet	0.8	274	128	53
Refugio	Duet	0.8	1,354	967	28.6
San Patricio	Duet	0.8	1,668	736	55.9
Aransas	Duet	1	3,248	2,152	33.8
Calhoun	Duet	1	7,418	3,787	49
Jim Wells	Duet	1	74	36	51.4
Kleberg	Duet	1	148	90	39.2
Lavaca	Duet	1	356	123	65.4
Nueces	Duet	1	170	88	48
Calhoun	Dibrom	0.7	3,787	872	77
Hardin	Dibrom	0.7	5,589	42	99.2
Jackson	Dibrom	0.7	1,289	573	55.5
Jasper	Dibrom	0.7	3,213	257	92
Jefferson	Dibrom	0.7	174	29	83.3
Liberty	Dibrom	0.7	4,565	1,412	69.1
Montgomery	Dibrom	0.7	2,542	323	87.3
Newton	Dibrom	0.7	8,612	302	96.5
Orange	Dibrom	0.7	251	15	94
Polk	Dibrom	0.7	2,458	71	97.1
Sabine	Dibrom	0.7	805	44	94.5
San Jacinto	Dibrom	0.7	1,207	94	92.2
Walker	Dibrom	0.7	1,738	49	97.2
Waller	Dibrom	0.7	16,376	404	97.5
Wharton	Dibrom	0.7	1,179	550	53.3

[1] CDC, Centers for Disease Control and Prevention.

and 1% application rates resulted in 49% and 69% control of *Ps. columbiae*, respectively. For *Culexnigripalpus* only the 1% Duet application rate applied (none of this species were collected in counties that received the 0.8% Duet application) and resulted in 59% control.

DISCUSSION

In total, 79 aerial spray missions were conducted over a 17-day period following Hurricane Harvey. Though the percent control varied by product and application rate, the responders and people burdened by the large nuisance mosquito populations provided positive feedback to their respective EOC. The approval of the EOCs and posttrap surveillance numbers were the factors that were used to mark the STARs as complete and to end the aerial missions.

Following the 2004 hurricane season in Florida, Simpson (2006) reported 69.7% control for *Ps. columbiae* and 64.1% for *Cx. nigripalpus* using Dibrom. Breidenbaugh et al. (2008) saw a slight decline in light trap collections following a spray mission in eastern Texas but reported statistically significant reductions (90%) in LRCs after aerial applications of Dibrom following Hurricane Rita. These authors also found *Ae. atlanticus* and *Ae. vexans* to be major contributors to mosquito biting pressure along with *Cx. nigripalpus* and *Ps. columbiae*. However, their study site was located farther north than the locations discussed here. For the current response, the Dibrom applications exceeded Florida's efficacy results for both species of interest with 95% of *Ps. columbiae* and 93% control of *Cx. nigripalpus*. The 1% application rate of Duet achieved similar results for *Ps. columbiae* and *Cx. nigripalpus* as the Dibrom applications in 2004 in Florida. The differences in control reported by insecticide in the current study could be due to several variables, including ambient temperature and the target insect population's relative resistance.

Public health is the primary driver for this type of response, reducing the potential for disease transmission and easing the mosquito biting pressure while electrical power is being restored, responders are working outdoors, and cleanup measures are deployed. However, fiscal responsibility still must play a role. Considering the size of the areas involved, small changes in pesticide quantity can increase overall costs significantly. At the same time, a tremendous number of resources being brought together, such as aircraft, staff, and scientific expertise, all play a role in the response and are time critical. Additionally, the areas will likely be sprayed only once, so it is important to have efficacious treatments that are also time sensitive. Applying at maximum label rate may be a simple way of attempting to maximize results, but if a lower amount achieves a similar standard, then the maximum rate is wasteful. The 0.7 ounce/acre rate was previously successful against *Ps. columbiae* in western Louisiana following Hurricanes Katrina and Rita in 2005 (Breidenbaugh and Haagsma 2008) and worked well in east Texas during the current response. This underscores the importance of maintaining proper integrated pest management procedures, even during emergency responses. Our advice to other public health officials faced with similar decisions is to start the application rate near the maximum based on the overall starting densities of mosquitoes and look at the efficacy data as soon as is feasible. The rate can be adjusted up or down based on those results.

The Coastal Bend area received much less rainfall than the areas in east Texas, resulting in a large emergence of *Ae. taeniorhynchus*. A variety of floodwater mosquito populations have the potential to surge following hurricanes (Goddard 2013), and subsequent pest management is time sensitive if the public is going to be protected from unacceptable levels of mosquito biting pressure. Aerial spraying was conducted by DSHS for precisely this reason, to manage the large numbers of mosquitoes impeding recovery efforts, as indicated by the pretrapping numbers of *Ae. taeniorhynchus* in the Costal Bend area.

The hurricane produced large populations of this species, and the first aerial applications were initiated to target *Ae. taeniorhynhcus*. However, based on our data it appears that *Ae. taeniorhynchus* populations emerged prior to the other floodwater mosquito populations, resulting in the need for additional aerial applications in the Coastal Bend area. Furthermore, since the contractors were covering large parts of the state with surveillance activities to support the aerial missions, trap locations were selected in real time without the benefit of historical knowledge of the area and mosquito habitat. The trap locations had to fall within the spray blocks and may not have represented the areas where mosquito emergence was occurring due to the FEMA guidelines of targeting large population centers and areas where first responders were on the ground. Thus, applications would knock down only the mosquito populations moving into the spray areas and not target the actual mosquito habitat, potentially resulting in less control.

The rapid response by contractors and the USAF assets along with the excellent results and public health benefits from mosquito control illustrate the functionality of the national capability for large-area mosquito control following natural disasters. In this instance, local and public resources were either incapacitated or quickly reached maximum capacity for response, which triggered the request for federal resources regarding aerial spraying by the USAF. In future responses, vector surveillance could potentially be supplemented by the federal government, including the Department of Defense, if available contractor resources are limited (Lindroth EJ, Breidenbaugh MS, Stancil JD, unpublished data). The Texas Hurricane Harvey response showcased how effective federal, state, local, and private assets can be in providing a stop-gap measure to control mosquitoes while local vector control agencies return to full capacity following a natural disaster.

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